GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

(R5508-4A0)
Project No. E-16-625 (Continuation of E-16-687) GTRC/~~GIT~~ DATE 6 / 20/ 86

Project Director: ~~Dr. A. L. Ducoffe~~/Dr. R.B. Gray / D.P. SCHRAGE School/~~Lab~~ Aerospace Engr.

Sponsor: U.S. Army Research Office
Research Triangle Park, NC 27709

Type Agreement: Mod. P00007 to SFRC DAAG29-82-K-0094

Award Period: From 7/1/84 To ~~6/30/87~~ 12/31/87 (Performance) ~~8/30/87~~ 1/30/88 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 1,008,000
Funded:	$	$ 1,008,000

Cost Sharing Amount: $ 100,800 Cost Sharing No: E-16-387(F5508-4A0)

Title: A Center of Excellence for Rotary Wing Aircraft Technology

ADMINISTRATIVE DATA

OCA Contact John Schonk X-4820

1) Sponsor Technical Contact:

Dr. Robert E. Singleton
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709

2) Sponsor Admin/Contractual Matters:

Mr. Abram J. Van Hall, Contracting Officer
(Same address as on left) 919-549-0641
For all matters except as covered by ONR RR.
Mr. T.A. Bryant, ONR RR
(Property, patent, invoice & closing matter)
Campus

Defense Priority Rating: N/A

Military Security Classification: Unclassified
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached SFRC Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT (Prior sponsor approval required for purchase of additions to equipment).

COMMENTS:

Mod. P00007 adds 5th year funding through 6/30/87. New project number assigned for GIT accounting purposes. NOTE: Account No. E-16-521 (P5045-0A0) has been established for payment of fellowships. No separate paperwork will be distributed for this account. Total contract amount for this project is $5,308,000.

JUN 1986 RECEIVED REPORT SERVICES

COPIES TO:

SPONSOR'S I. D. NO. 02.102.001.86R41

Project Director	Procurement/GTRI Supply Services	GTRC
Research Administrative Network	Research Security Services	Library
Research Property Management	**Reports Coordinator (OCA)**	Project File
Accounting	Research Communications (2)	Other A. Jones

FORM OCA 65:285

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 4/6/88

Project No. E-16-625 School/~~Lab~~ AE

Includes Subproject No.(s) N/A

Project Director(s) R. B. Gray GTRC/~~GIT~~

Sponsor ARMY

Title A CENTER OF EXCELLENCE FOR ROTARY WING AIRCRAFT TECHNOLOGY

Effective Completion Date: 12/31/87 (Performance) 2/29/88 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Copy of Last Invoice Serving as Final
- [X] Release and Assignment
- [X] Final Report of Inventions and/or Subcontract: Patent and Subcontract Questionnaire sent to Project Director [X]
- [X] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. E-16-A02 Continued by Project No.

COPIES TO:

Project Director
Research Administrative Network
Research Property Management
Accounting
Procurement/GTRI Supply Services
Research Security Services
Reports Coordinator (OCA)
Program Administration Division
Contract Support Division

Facilities Management - ERB
Library
GTRC
Project File
Other

PROGRESS REPORT

1. **ARO PROPOSAL NUMBER**: 19364-EG-RW

2. **PERIOD COVERED BY REPORT**: 1 JULY - 31 DECEMBER 1986

3. **TITLE OF GRANT NUMBER**: A CENTER OF EXCELLENCE FOR ROTARY WING AIRCRAFT TECHNOLOGY

4. **CONTRACT OR GRANT NUMBER**: DAAG29-82-K-0094

5. **NAME OF INSTITUTION**: GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF AEROSPACE ENGINEERING

6. **AUTHOR(S) OF REPORT**: R.B. Gray, J.I. Craig, S.V. Hanagud, S.S. Klein, N.M. Komerath, H.M. McMahon, S.A. Meyer, D.A. Peters, G.A. Pierce, N.L. Sankar, D.P. Schrage, L.W. Rehfield, J.C. Wu

7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES**:

Publications:

1. Hodges, R.V., Nixon, M.W. and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastran Shell Element Model," NASA Technical Memorandum - 89024, January 1987.

2. Bauchau, O., Coffenberry, B.S. and Rehfield, L.W., "Composite Box Beam Analysis: Theory and Experiments," Journal of Reinforced Plastics and Composites, January 1987.

3. Pierce, G. Alvin and Klein, Steven S., "A Unique Approach to Aeroelastic Testing of Scaled Rotors," submitted to Vertica.

4. Pierce, G. Alvin and Klein, Steven S., "A Unique Approach to Aeroelastic Testing of Scaled Rotors," Twelfth European Rotorcraft Forum, Garmisch-Partenkirchen, Feceral Republic of Germany, September 22-25, 1986.

5. Brand, A.G., Komerath, N.M., McMahon, H.M. : "Wind Tunnel Data From a Rotor Wake/Airframe Interaction Study". Wind Tunnel Report, Georgia Institute of Technology, July 1986.

6. S. Hanagud, M. Meyyappa, Y.P. Cheng, and J.I. Craig, "Identification of Structural Dynamic Systems With Nonproportional Damping," AIAA Journal, Vol. 24, Nov. 1986., pp. 1880-1882.

7. S. Hanagud and M.W. Obal, "Optimal Vibration Control by the Use of Piezoceramic Sensors and Drivers," to be presented at the 28th AIAA/ASME/AHS/ASEE SDM Conference, Monterey, California, April 1987.

8. S. Hanagud and B.J. Glass, "Structural Dynamic Model Identification Using Heuristic Search," to be presented at the 28th AIAA/ASME/AHS/ASEE SDM Conference, Monterey, California, April 1987.

9. Nygren, K. P., Advisor-Schrage, D. P., "An Investigation of Helicopter Higher Harmonic Control using a Dynamic System Coupler Simulation", PhD Thesis, Georgia Institute of Technology

10. W. Tang and L. N. Sankar, "Strong Blade-Vortex Interactions Including Collision", Submitted to the Forum on Unsteady Flow Separation, ASME Fluids Engineering Spring Conference, June 1987, Cincinnati, OH.

11. D. P. Schrage and S. A. Meyer, "VTOL Operational Considerations and Their Impact on Future Military Design Requirements", AIAA/AHS/ASEE Aircraft Systems, Design & Technology Meeting, October 20-22, 1986, Dayton, OH. AIAA # 86-2649

12. D. P. Schrage and S. A. Meyer, "Rotorcraft Preliminary Design Education", AIAA/AHS/ASEE Aircraft Systems, Design and Technology Meeting, October 20-22, 1986, Dayton, OH. AIAA# 86-2748

13. J. Berry and D. P. Schrage, "Rotor Design for Maneuver Performance, submitted to <u>Vertica</u>. Presented at Twelfth European Rotorcraft Forum, Garmisch - Partenkirchen, Federal Republic of Germany, September 22-25, 1986

<u>Presentations</u>

1. Rehfield, L.W., "Some Observations on the Behavior of the Langley Model Rotor Blade," USA Aerostructures Directorate, Langley Research Center, Hampton, VA, 24 July 1986.

2-3. Rehfield, L.W., "Structural Technology for Elastic Tailoring of Rotor Blades, presented at:

- Army Research Office, Durham, NC, 25 September 1986.
- USA Aeroflightdynamics Directorate, Ames Research Center, Moffett Field, CA, 29 September 1986.

4. Chan, W.S. and Rehfield, L.W., "Analysis, Prediction and Prevention of Edge Delamination in Rotor System Structures," RPI Workshop on Composite Materials and Structures for Rotorcraft, Troy, NY, 10-11 September 1986.

5. Rehfield, L.W., Reddy, A.D. and Daniel, W.K., "Postbuckled Composite Primary Structure: Creating the Technology Base," RPI Workshop on Composite Materials and Structures for Rotorcraft, Troy, NY, 10-11 September 1986.

6. Rehfield, L.W., "Synergistic Structural Technology for Rotor Systems," Bell Helicopter Textron, Ft. Worth, TX, 23 September 1986.

7. Hodges, D.H. and Rehfield, L.W., "Effect of Composite Blade Elastic Couplings on Stability," USA Aerostructures Directorate, Langley Research Center, Hampton, VA, 12 November 1986.

8. Rehfield, L.W., and Atilgan, Ali, R., "Analysis of Multicell Thin-Walled Composite Beam Structures," USA Aerostructures Directorate, Langley Research Center, Hampton, VA, 12 November 1986.

9. Rehfield, L.W., Armanios, E.A. and Weinstein, F., "Understanding and Predicting Sublaminate Damage Mechanisms in Composite Structures," Bell Helicopter Textron, Ft. Worth, Tx, 11 December 1986.

10. Schrage, D. P., Loewy, R. and Gessow, A., "Rotorcraft COE's Presentation at ARO", November 17, 1986

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Principal Investigator: R.B. Gray

Faculty: J. I. Craig, S. V. Hanagud, N. Komerath, H. M. McMahon, D. A. Peters, G. A. Pierce, L.W. Rehfield, N.L. Sankar, D. P. Schrage & J.C. Wu

Research Engineers: S. S. Klein, R. Latham, S.A. Meyer

Research Associates: J. Caudell & H. Meyer

Post Doctors: V.R. Anand, M. Meyyappa, & C. Wang

Fellows: Ph.D.: Albert G. Brand, M. W. Heiges, Dimitrios N. Mavris, Dana J. Taylor, Thomas L. Thompson,
Dana J. Taylor, Brian Wake, and Mark E. Wasikowski

M.S.: Chris Fouts, Jeff W. Harding

Graduate Research Assistants: Ph.D.: N.S. Abhyankar, R. Chander, Y.Cheng, W.K. Daniel, M. Hashemi-Kia, V. M. Kaladi, Y.K. Kim, O.J. Kwon, S.G. Liou, M. T. Patterson, S. Sarkar, P. Sriram, W. Tang, I. Tuncer, C.C. Won, Y.K. Yillicki W. Zhou

Graduate Research Assistants: M.S.: B. Glass, R. Jolly, J.L. Kemnitz, R. Kisor, L.S. Mayer, H.E. Mersinoglou, R. Srivastava

CONTRIBUTED TO PROJECT BUT WERE NOT SUPPORTED

Faculty: D. H. Hodges

Research Engineer: V.R.P. Jonnalagadda

PhD Students: LTC K.P. Nygren

M.S. Students: MAJ M. Obal, O. Schreiber

DEGREES AWARDED (THIS REPORTING PERIOD)

NAME	DEGREE-DATE	PRESENT AFFILIATION
J. E. Corban	MS - Sept 1986	PhD Program Georgia Tech
W. K. Daniel	MS - Dec 1986	Vought Corporation
C. L. Fouts	MS - Sept 1986	PhD Program Georgia Tech
J. W. Harding	MS - Sept 1986	McDonnell Douglas HC
M. W. Heiges	MS - Sept 1986	PhD Program Georgia Tech
M. Hashemi-Kia	MS -	PhD Program Georgia Tech
A. P. Izadpanah	PhD - Dec 1986	NASA Langley
J. R. Jolly	MS - Sept 1986	
J. L. Kemnitz	MS - Sept 1986	PhD Program Georgia Tech
L. S. Mayer	MS - Dec 1986	
LTC K. P. Nygren	PhD - Dec 1986	USMA Faculty
M. T. Patterson	MS - Sept 1986	PhD Program Georgia Tech
O. Schreiber	MS - Sept 1986	PhD Program Georgia Tech
R. Srivastava	MS - Dec 1986	
T. L. Thompson	PhD - Dec 1986	McDonnell Douglas HC
M. E. Wasikowski	MS - Sept 1986	PhD Program Georgia Tech

DEGREES AWARDED (CUMULATIVE)

NAME	DEGREE-DATE	PRESENT AFFILIATION
V.R. Anand	PhD - Dec 1982	Georgia Tech
A.G. Brand	MS - Sept 1985	PhD Program Georgia
T. Boyd	MS - Sept 1983	US Air Force
C. Boyette	MS - Dec 1983	McDonnell Douglas HC
C. Brevoort	MS - Sept 1983	Lockheed Georgia
CPT C.N. Cardinal	MS - June 1984	US Army
H.P. Chen	PhD- Dec 1983	Georgia Tech
MAJ M. Clifford	MS - Dec 1982	US Army
J.E. Corban	BAE- June 1983	McDonnell Douglas HC
	MS - Sept 1986	PhD Program Georgia Tech
W. K. Daniel	MS - Dec 1986	Vought Corporation
P.L. Elliot, III	BAE- June 1983	Boeing Vertol Co.
K. Engelhardt	MS - Sept 1983	McDonnell Douglas
C. Fouts	MS - Sept 1986	General Dynamics
P.J. Georges	MS - Sept 1984	
C. Grimmell	MS - June 1984	General Dynamics
B.A. Gustavson	MS - Sept 1982	Kaman Aerospace

J. W. Harding	MS - Sept 1986	McDonnell Douglas HC
M. Hashemi-Kia	MS -	PhD Program Georgia Tech
MAJ W. J. Hatch	MS - June 1984	US Army
M. W. Heiges	MS - Sept 1986	PhD Program Georgia Tech
J.A. Humphries	MS - June 1984	US Air Force
A. Izadpanah	PhD - Dec 1986	NASA Langley
R. Jolly	MS - Sept 1986	
V.R.P. Jonnalagadda	MS - Sept 1983	
	PhD- Sept 1985	Georgia Tech
V.M. Kaladi	MS - Sept 1985	PhD Program Georgia Tech
J.L. Kemnitz	MS - Sept 1986	PhD Program Georgia Tech
Y.K. Kim	MS - Sept 1985	PhD Program Georgia Tech
S.G. Liou	MS - Sept 1985	PhD Program Georgia Tech
L. S. Mayer	MS - Dec 1986	
D. Mavris	MS - Sept 1985	PhD Program Georgia Tech
CPT W. McArthur	MS - March 1983	US Army
LTC K.P. Nygren	PhD - Dec 1986	USMA Faculty
P. Oliver	MS - June 1985	McDonnell Douglas HC
D. O'Neil	MS - Sept 1984	McDonnell Douglas HC
T. Parham	MS - Sept 1983	Bell Helicopter Textron
M.T. Patterson	MS - Sept 1986	PhD Program Georgia Tech
M. Pollack	BAE - June 1986	MS Program Georgia Tech Graduate Co-op Sikorsky Aircraft
G. Power	MS - Sept 1983	United Technologies Research Center
D. Pritchard	MS - Sept 1984	PhD Program Georgia Tech Graduate Co-op McDonnell Douglas HC
J. Rogers	MS - Sept 1983	General Dynamics
O. Schreiber	MS - Sept 1986	PhD Program Georgia Tech
S. Sparks	MS - Sept 1983	United Technologies Research Center
R. Srivastava	MS - Dec 1986	
D.J. Taylor	MS - Sept 1984	PhD Program Georgia Tech
T. Thompson	MS - Sept 1983	
	PhD - Dec 1986	McDonnell Douglas HC
R.R. Tipton	MS - Aug 1983	McDonnell Douglas HC
B. Wake	MS - Sept 1984	PhD Program Georgia Tech
M.E. Wasikowski	MS - Sept 1986	PhD Program Georgia Tech
T. Wey	PhD- Dec 1983	Lockheed-EMSCO, Inc.

RESEARCH TASKS

I. Aerodynamics

Task 1. Experimental Studies for Tip Vortex Core Modeling

R.B. Gray, N.M. Komerath, T.L. Thompson, J.L.Kemnitz, O.Kwon

The objectives of this task are to develop a capability for measuring the flow field near the tip and in the wake of a hovering helicopter model rotor using a laser velocimeter and to use the data to guide the development of a tip vortex core model for use in free wake analyses for blade loading predictions. The longer term objectives are to develop a hovering vortex wake analysis which is not as dependent on empirical parameters for describing the tip vortex geometry and to investigate the extension of the vortex wake analysis to low-speed forward flight.

During the last reporting period, the measurement program in the tip vortex core was completed, and a Ph.D. thesis was written and defended on the work of the past four years. Data were obtained on the axial velocity component inside the core of the moving tip vortex in the near wake, which represents a new contribution that should aid in the improvement of core models.

Work on quantifying and correcting for errors due to seed particle spin-out effects continues. An algorithm was developed which, given the measured particle velocity field (this is what the LDV actually measures) and the mean seed particle size and properties, could iteratively arrive at the actual **fluid** velocity field. The feasibility of this procedure was demonstrated computationally using an assumed potential flow field around a source in a uniform stream, and exaggerated particle inertia effects. Convergence was obtained. This is now being extended to the case of a vortex. When successfully demonstrated, this algorithm will be used, along with the measured vortex core data and measured seed particle size, to estimate and then correct for lag errors. Preliminary studies of the measured vortex core data obtained using incense seeding and off-axis scatter indicate, however, that radial velocity values in the vortex are acceptably low, indicating that the errors are small.

A panel code has been developed to predict pressure distributions over the blade in low-speed forward flight with low computational cost. Information from the distorted far wake is obtained from the existing lifting line code. The rotor blade surface is represented by a distribution of surface sources and normal doublets. As a first step, the case of a non-lifting rotor was calculated and compared with existing experiments. Good agreement was obtained, as shown in figure 1. As the next step, rotor blades with effective angle of attack are being tested.

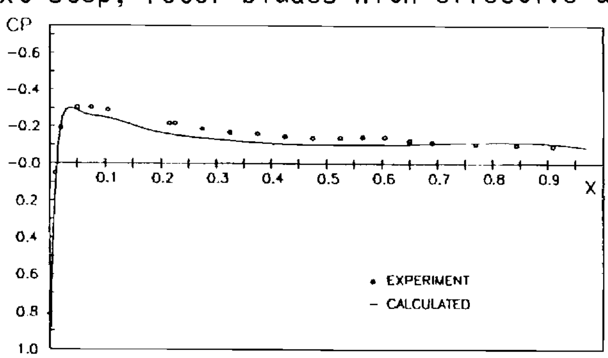


Figure 1. Comparison of Calculated Pressure Distribution of a Non-lifting Rotor at Hover with Experiment at 99.5% Spanwise Station.

Figure 1

One Ph.D. thesis, an M.S. Special Problem report, and one AIAA Conference paper were completed during this reporting period. Some of the results were also presented at a seminar given by Komerath at United Technologies Research Center. A paper is being written for submission to a journal.

Task 2. Modification of Blade Tip Loading to Improve Hovering Figure of Merit

R.B. Gray & T. Thompson

Measured pressure distributions on the tip of a hovering model rotor blade show a low pressure region which is associated with the roll-up and rearward sweep of the tip vortex over the trailing 50% for the blade upper surface. This low pressure region near the trailing edge contributes significantly to the section pressure drag and hence to the rotor power required. The objective of this task is to explore the possibilities of improving performance by modifying the tip pressure distribution.

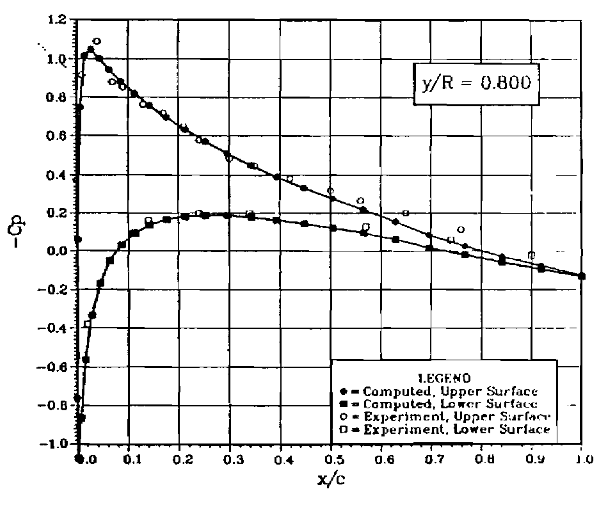
This research task has been completed and a final report will be prepared.

Task 3. Prediction of Flow Around Blade Tips

R. B. Gary, L.N. Sankar and B. E. Wake

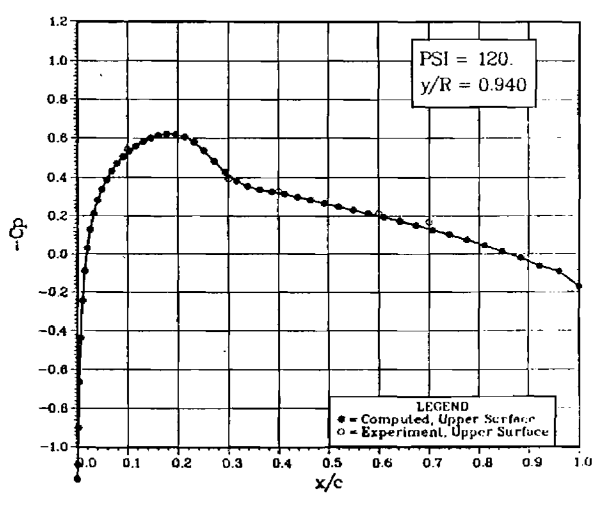
The objective of this task is to develop a procedure to accurately predcit the flow field, and hence the airloads in the vicinity of the tip of a rotor blade. This requires an accurate modeling of the vortex formation, and roll up processes, and the strength and location of any shocks.

Calculations were performed for a NACA 0012 rotor in hover, at 8 degree collective pitch angle, and a tip Mach number equal to 0.44. The angle of attack corrections due to the portions of the vortex not captured by the computational grid were computed from the CAMRAD code. Good correlation with the experiments have been obtained over the entire blade span.



Hovering two-bladed rotor with 0012 airfoil sections, hover tip Mach number of 0.44, collective pitch of 8.0 degrees, and aspect ratio of 6.0.

Figure 1



ONERA Blade with an advance ratio of 0.45 and a hover tip Mach number of 0.60.

Figure 2

Calculations have also been performed for an ONERA tapered blade at high enough forward speeds and tip Mach numbers to produce strong shock waves in the vicinity of the tip. The surface pressures computed by the Navier-Stokes code have been compared with experiments, our earlier Euler calculations, and other numerical results. It was found that among the variety of numerical techniques available for this problem, the Navier-Stokes results provide the best agreement with experiments.

Since the 3-D Navier-Stokes solver must use reasonably small computer times to be of benefit to the rotorcraft industry, some effort was also initiated to improve the computer time requirements, and to increase the time step used by the flow solver. A Newton iteration technique is being pursued for increasing the time step by a factor of ten. Should this be successful, the Navier-Stokes solver would require roughly 2 hours on a CRAY-XMP to carry out the calculations for one full revolution of the rotor blade.

The calculations discussed above will be presented at the AHS Specialists Meeting on Aerodynamics and Aerodynamics, in February 1987.

Task 4. Studies of Unsteady Rotor Aerodynamics

J. C. Wu, N.L. Sankar, M. Patterson, R. Srivastava, I. Tuncer

The purpose of this task is to develop theoretical and computational tools for the prediction of the unsteady airloads on modern rotor blades in hover and in forward flight.

The 2-D incompressible zonal Navier-Stokes solver was validated against experimental data of McAlister and McCroskey for a wide range of reduced frequencies. It was verified that the Navier-Stokes solver captures accurately the physical phenomena, and in particular the shedding of strong leading and trailing edge vortices. Parametric studies related to grid sensitivity, and turbulence modeling were also carried out to arrive at an optimum grid which captures all the features of dynamic stall well. A numerical conformal mapping procedure was integrated into the flow solver, allowing it to handle any arbitrary airfoil shape.

No additional work was done on the 2-D compressible Navier-Stokes solver. Support was provided to Government users (Larry Carr; Jim Valdes) and Industry users (Steve Podleski: Bell Helicopters) to customize the Navier-Stokes solver for their individual needs.

Task 5. Studies of the Airframe Flowfield in Forward Flight

H.M. McMahon, N.M. Komerath, A. Brand, D. Mavris, S.G. Liou, R. Kisor

The long-term objective of this task is the development and validation of a reliable technique for predicting the coupling between rotor and airframe aerodynamics. The short term goals are to provide a data base for developing and assessing analytical models, to assess existing analytical models, and to investigate the flow features important in rotor-airframe aerodynamics.

Another series of wind tunnel tests in forward flight were conducted during the Fall of 1986; following calibration of the wind tunnel external balance.

Several gaps in the airframe surface pressure data were filled and then attention turned to measurements in the flowfield. The probe actuator was installed and a procedure was developed for determining the location of the edge of the rotor wake using a Kiel pressure probe. Using this technique, the deflected wake location was found for the case of the rotor in forward flight (no airframe). These measurements will be useful for comparison with prediction from the rotor codes now under investigation. With the airframe in place in the flow this pressure technique did not yield a satisfactorily precise measure of the wake shape. Attention then turned to flow visualization techniques using a laser light sheet. Seeding of the flow has already been successfully accomplished for the LDV measurements using oil droplets. In the center of a vortex these droplets are centrifuged away leaving a dark spot in an otherwise illuminated region. This flow visualization approach has yielded excellent data as regards the location of the vortices shed by the rotor tips. The use of stroboscopic laser light allows correlation of the location with blade position, while superposition of a grid in the video camera frames allows for satisfactorily accurate determination of location.

In addition to quantitative vortex trajectory location, the flow visualization program yielded some interesting footage of the dynamics of vortex dynamics including the motion induced by the passage of the rotor, interaction between vortex spirals, and interaction of vortices with the airframe surface.

A preliminary study of turbulence intensity in the undisturbed tunnel flowfield was performed using hot-wire anemometry. This revealed that the intensity has been drastically reduced by the flow quality improvements performed in the tunnel. Comparison of mean velocity data between the hot-wire and LDV showed excellent agreement; comparison of turbulence intensities yielded the expected result that intensities measured by the LDV were slightly higher than those measured with the hot-wire. This is considered to be a satisfactory benchmark comparison in this configuration, because a closed-loop test has been achieved which involves all the optical and electronic hardware and the data acquisition programs.

The field of view of the LDV in the tunnel was extended by modifying test section window arrangements.

LDV surveys of the flow field between the rotor and airframe were conducted, repeating previous measurements. Repeatability is satisfactory. The tip path plane angles of the rotor were measured again with the LDV, and these matched previous measurements to within .25% (.01 degrees). Data acquisition in a plane at a fixed distance of 12.7mm below the rotor plane was then undertaken. Constraints of run time dictated selection of measuring locations and priorities to some extent. A hardware failure in the traverse system forced a somewhat early departure from the tunnel in December, so that the data set is incomplete at this point. In view of the excellent repeatability of conditions, it is expected that the data set will be completed early in the next entry into the tunnel.

Following a survey of the existing literature on rotor and airframe aerodynamics codes, it was decided that Scully's free wake rotor code would be integrated with the VSAERO body code to provide a new rotor-airframe interaction code. This would take advantage of the features of the VSAERO code, as well as provide the capability to get azimuth-resolved flowfield results and flow-body interaction features. Scully's code has been made operational on the Georgia Tech CYBER, and automated iterative running capabilities are being developed. Meanwhile, the results from Scully's code for the rotor alone are being validated using existing exeperimental data. The interaction algorithm is also being developed.

II. Structures

Task 1. Structural Dynamic System Identification

S.V. Hanagud, J.I. Craig, N.S. Abhyankar, A. Chattopadhyay, M. Meyyappa, Y. Cheng, M. Obal, S. Sarkar, O.J. Kwon, Y.K. Yillicki

The purpose of this task is to develop an approach to advance the state of the art in airframe structural dynamic modeling. Development of applicable system identification techniques - the mathematical model of the system of interest - and improved physical models are the basis for this research.

General directions of this phase of the project are to develop accurate analytical models for the dynamic behavior of a rotorcraft from a knowledge of the experimental results and preliminary models. During the previous contract period, it has been shown that a study of the identification of distributed parameter systems will significantly enhance the capability of modeling airframe, rotor and coupled rotor/airframe models.

Therefore, structural dynamic system identification techniques are being developed to evaluate the properties of continuous or distributed parameter systems. In contrast with discrete systems which are described by a set of matrix coefficients, distributed systems possess infinite degrees of freedom and are usually modeled by means of partial differential equations with appropriate boundary and initial conditions. Identification of such systems consists of determining the parameters appearing in the differential equations and/or boundary conditions. In the most general case, these parameters will be spatially dependent within the domain of the structure. Identification techniques using time and frequency domain input-output data are currently being explored. An application is the identification of rotor blade models in helicopters. Since several formulations of rotor blade behavior have been proposed, it may be possible to use the techniques developed here, in conjunction with experimental data, to compare the various approaches and identify the formulation that is most accurate.

Work is also in progress in considering practical applications and validation of the identification procedures developed for discrete degrees of freedom. A detailed NASTRAN model is being developed for a UH-1H tailboom. Results from this model will be compared to the modal parameters of the tailboom determined experimentally. Reduced regions of this detailed model will also be used as a priori models in several identification procedures to obtain improved analytical models capable of reproducing the test data.

A Ph.D. thesis is being written in the field of identification of systems with general damping matrices. Three new procedures have been presented in the thesis. Applications to large dynamical systems like an airframe are being evaluated.

Two additional Ph.D. theses entitled (1) "Studies in Nonlinear Structural Dynamics" and (2) "Vibration Control of Flexible Structures by Piezoceramic Sensors and Actuators" have been completed during the project period.

Task 2. Crashworthy Characteristics of Composite Rotorcraft Structures
S.V. Hanagud, R. Chander, B. Glass, L.S. Mayer, P. Sriram, W. Zhou

The objective of this task is to conduct basic research to develop improved techniques and procedure for designing crashworthy composite structures for rotorcraft. This objective includes the development of testing techniques and optimization of the crashworthy designs under the constraints of weight restrictions, cost and performance requirements.

During this project period the study has focused on graphite-epoxy curved web structures as candidate energy absorbing structures. The family of structures that are being studied are made of circular arc segments. The included angles of the segments varied in the range of 90° to 180°. The experimental study obtained the variation of specific energy absorption as a function of these included angles. In addition to the study of specific energy absorption of these graphite-epoxy curved web specimens, tests were interrupted at different levels of failure to examine (a) the nature of the brittle fracture of these specimens (b) microscopic examination near the progressive collapse and (c) extent of the damaged zone next to the loading surface.

A finite element model is being formulated to study the loading and progressive failure of the graphite-epoxy curve web structure. The first phase of the program has been completed. At present, a study of the "on-set" of the fracture is being investigated.

The design and development of the device to measure dynamic force-deformation relationships of the energy absorption structure has been completed. The device has been validated to ensure the capture of the initial peak preceding the progressive collapse of the energy absorbing structure. At present, work is in progress to validate the device beyond the "initial peak." This constitutes the first phase of the work in studying the sensitivities of the KRASH program and development of predictive capabilities for use in the preliminary design.

Technical discussions have been held with Mr. J. Cronkhite of Bell Helicopters, Mr. G. Farley of NASA, Mr. C. Kindervater of DFVLR and the technical personnel at MBB.

Task 3. **Concepts for Stability Critical Airframe Structures**

L.W. Rehfield, and W.K. Daniel

This task is concerned with crippling and postcrippling behavior of thin walled graphite/epoxy composite airframe members in axial compression. The main objectives are to i) generate an experimental data base on the crippling and postcrippling behavior, ii) develop simple analytical methods to predict these behavior, and iii) provide better insight into the failure processes for this type of structure.

Emphasis has been given to analysis and correlation with previous experiments in this period. A crippling law for no-edge-free composite plate elements has been created with a completely theoretical basis. Our experimental data agree fairly well with the theory. It is based upon a maximum strain failure criteria.

A simplified analysis of composite plate elements has been created and is currently being evaluated for one-edge-free configurations. A new variational formulation has been created to characterize the situation being modeled. Simple, approximate solutions are currently being sought based upon the variational principle developed.

A study has been undertaken to assess the influence of bending-twist coupling terms due to stiffnesses D_{16} and D_{26}. For practical layups of interest, we are finding corrections of less than 5 percent.

Task 4. **Composite Rotor Blade Modeling**

Lawrence W. Rehfield

The development of a theory valid for large deflections and moderate rotations has been completed. Due to the other new findings, this theory has not been exercised.

Our single cell theory has been improved. The improvements are related to twisting kinematics.

A study has been completed which thoroughly develops the basis for extension-twist coupling in blades, the primary form of coupling useful for tilt rotor applications. Among our important findings is the discovery that a single coupling parameter controls the structural design. General behavioral laws in terms of this parameter have been established.

III. Aeroelasticity

Task 1. **Helicopter Vibration Suppression Techniques**

G.A. Pierce, V. Anand, V.M. Kaladi, Y.K. Kim, D.J. Taylor

This program is intended to develop and validate comprehensive vibratory loads analyses for the evaluation of vibration suppression techniques. The loads analyses will be applicable to nonuniform multi-bladed systems with various hub constraints. Special emphasis will be placed on blade structural dynamics, hub and mast dynamics, and unsteady blade aerodynamics.

Two comprehensive methods of analysis have been developed for the determination of elastic rotor blade response in forward flight. Both of these analyses are sufficiently general to handle non-uniform blades with various parametric offsets. Results obtained from these methods have been correlated with each other and published data from other analytical studies.

The first method of analysis is based on a new formulation of the blade equations for flap-lag-torsion deformations. A unique aspect of this formulation is in the treatment of the pitch control inputs. A transformation for the collective and cyclic control is performed prior to the transformation from undeformed to deformed coordinates. This original approach has resulted in numerous coupling terms associated with pitch control inputs which are not present in other formulations. The spatial solution is obtained by a Galerkin technique with nonrotating modes, while the time dependency is computed by numerical integration.

The second method is an extension of the well-known structural dynamic development of Hodges and Dowell to include time-dependent pitch control inputs. This flap-lag-torsion representation has been programmed for solution using a harmonic balance technique by combining the previously used Galerkin approach with integer harmonic components for the generalized coordinates. This method provides two outstanding benefits. First, it is computationally very efficient; and secondly, it is ideally suited for the incorporation of unsteady aerodynamic formulations which are based on simple harmonic motion.

It should be noted that both of these analyses have been programmed for articulated and hingeless hub configurations. Work is currently progressing on the incorporation of bearingless pitch control inputs and constraints.

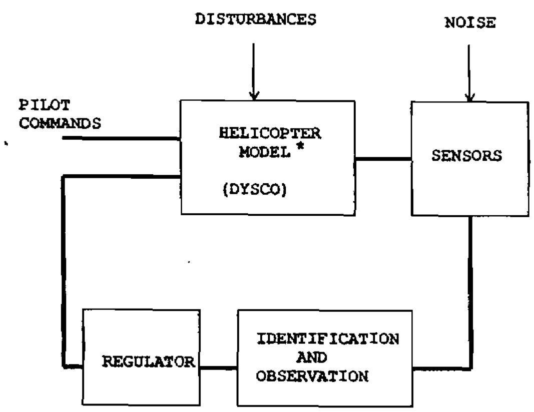
Task 2. Rotorcraft Aeroelastic Active Control Investigations

D.P. Schrage, D.A. Peters, M.E. Wasikowski, K.P. Nygren, V.R.P. Jonnalagadda

The purpose of the research in this task is to study, evaluate and compare the alternative controller configurations that have been shown either theoretically or experimentally to have the potential for providing favorable aeroelastic response. This research consists of both an analysis and an experimental program.

The analysis program consists of modeling the CERWAT Aeroelastic Rotor Test Chamber (AeroTech) with the RASA Aeroelastically Conformable Rotor (ACR) rotor blades installed and then evaluating a variety of controller configurations. Initially, the controller configurations were evaluated with respect to suppressing helicopter vibration. A flexible modeling system, the Dynamic Systems Coupler (DYSCO), was utilized to simulate the dynamic response of the OH-6A helicopter. The helicopter simulation model consisted of 12 rotor degrees-of-freedom and 6 fuselages degrees-of freedom. It included unsteady rotor aerodynamics along with simple fuselage aerodynamics. Five different higher harmonic control (HHC) regulators were evaluated which consisted of: a fixed gain, closed loop, local model; an adaptive, global model with identification of only the uncontrolled vibration; adaptive deterministic and cautious global models with identification of both the transfer matrix and the uncontrolled vibration; and a dual adaptive global model. A schematic of the general system layout is illustrated in Figure 1. A comparison of the controllers versus a performance index is illustrated in Figure 2.

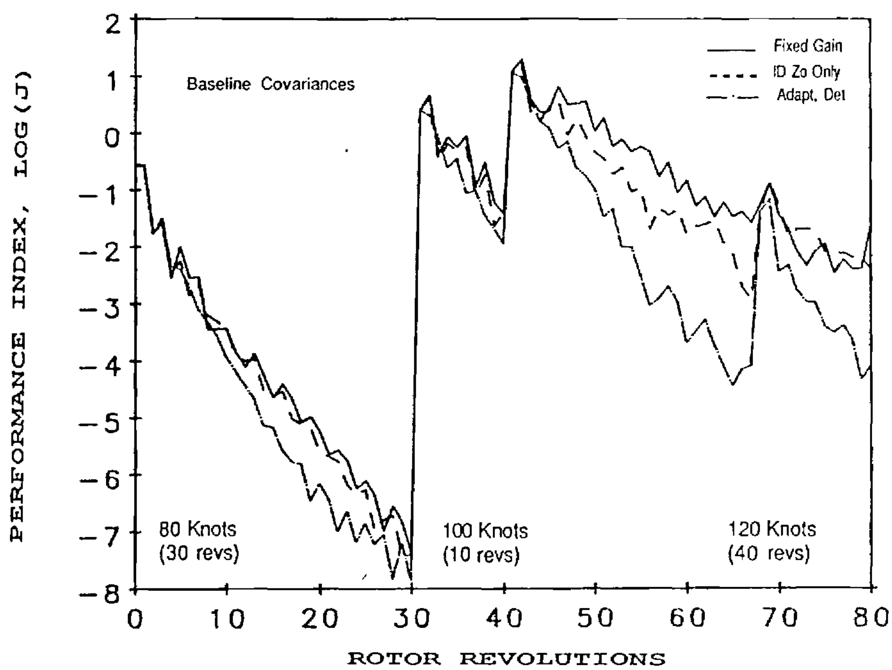
SYSTEM LAYOUT



* OTHER POTENTIAL IMPROVEMENTS IN MODEL FOR IBC:

EXCITATION - DYNAMIC INDUCED INFLOW MODULE
- LIFTING SUFACE THEORY MODULE
- STRUCTURAL DYNAMICS

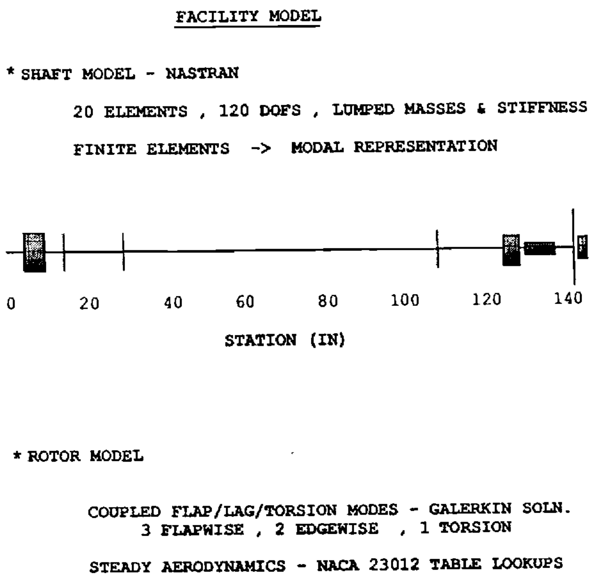
Figure 1



Two Step Maneuver - Trimmed at 80 to Trimmed at 100 to Trimmed at 120 Knots

Figure 2

Following the successful evaluation and verification of the controllers, they have been applied to the ACR rotor blades mounted in the CERWAT Aeroelastic Rotor Test Chamber. The facility model is illustrated in Figure 3. The rotor shaft was modeled using NASTRAN and then coupled with the rotor model using DYSCO. The various controllers were then applied to suppress four per revolution vibrations. An example of shaft axial response to swashplate excitation with the HHC controller turned on at the ninth rotor revolution is illustrated in Figure 4. Current plans are to obtain experimental results on AeroTech in the February-March 1987 timeframe.



* TOTAL MODEL DOFS - 27

Figure 3

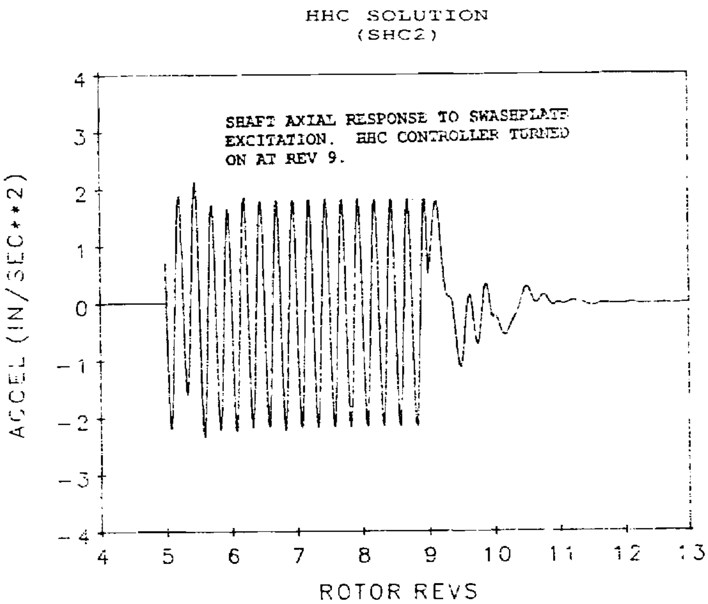


Figure 4

The second phase of the analysis effort is to model the McDonnell Douglas Helicopter Company (MDHC) HARP rotor system on AeroTech using a similar approach described for the ACR rotor blades. This modeling effort is currently being initiated.

Initial tests in the experimental program will consist of tests to compare and to unify the Loewy and dynamic-inflow theories, and to test the various controller regulator algorithms that have been previously analyzed. This program is scheduled to begin in February 1987, following the initial checkout of the facility.

FACILITIES/EQUIPMENT

I. Laser Doppler Velocimeter (LDV) Data Acquisition System

N.M. Komerath, R.B. Gray, H.M. McMahon

The four-beam, two-color Laser Doppler Velocimeter (LDV) consists of a five-watt Argon Ion Laser, modular optics, a three-axis traversing system, and two-counter type signal processors directly interfaced into the memory of a dedicated HP1000 computer system. Two orthogonal components of flow velocity can be measured simultaneously and nonintrusively, with a spatial resolution of 0.1 millimeters from a distance of over 2200 mm. Frequency shifting on both channels enables measurement of the velocity vector in recirculating flows and a field stop system enables measurements close to solid surfaces.

II. Nine-Foot Static Thrust Facility

R.B. Gray

The facility provides a laboratory-controlled environment for testing model helicopter rotors up to 4.5 feet in diameter in hovering flight. The LDV system described above is being used for data acquisition for Aerodynamics Task 1. The facility has also been used for Aerodynamics Task 2. The updating of this facility has included factory reconditioning of the mercury slip-ring assembly, which is now in progress.

III. Structural Dynamic System Identification Facility

S.V. Hanagud, J.I. Craig

This laboratory is developed to measure, record, process, and analyze structural dynamic data for laboratory model tests and field tests. The multichannel time series and structural dynamic analyzer allows acquisiton of data from one to eight channels simultaneously with the capability to expand to sixteen. The analysis software may run on the dedicated computer system or is portable to another system.

IV. Transient Dynamic Stress Analysis Facility

S.V. Hanagud, J.I. Craig

This facility is for the study of the dynamic behavior of structural components and assemblies under typical crash-induced loading situations for helicopters. The design of the facility involves a drop-test fixture for producing dynamic compressive loading of various metallic and composite test articles. A variety of waveform recorders acquire data during investigation of crashworthy characteristics of rotorcraft structures, particularly composite structures.

V. Seven-by-Nine Foot Forward Flight Facility

J.J. Harper, H.M. McMahon, & S.S. Klein

The closed low speed wind tunnel is the forward flight facility with a seven-by-nine foot test section. The design and installation of a powered model rotor system, fairings, floor, ceiling and honeycomb provide a total laboratory environment. The rotor system is mounted from the test section ceiling and fuselage models are mounted on a force balance sting. The Laser Doppler Velocimeter, a dedicated computer system and a modern force balance provide for data acquisition.

VI. **Aeroelastic Rotor Test Chamber (AeroTech)**

G. A. Pierce, S. Klein and M. Hashemi-Kia

The primary purpose of AeroTech is to experimentally simulate and record various aeroelastic phenomena associated with contemporary helicopter systems. The information compiled with this facility will form a valuable data base with which to correlated the predictions obtained from newly developed analytical techniques.

This facility has a computer-based data acquistion system which can simultaneously receive, condition, record and analyze up to 48 channels of response parameters. The on-line analysis of these data can be preprogrammed in FORTRAN 77 or processed by a time-series analyzer. The facility also has a three-channel hydraulic excitation system which permits on-line computer control of a swashplate mechanism for the dynamic excitation and control of the model rotor in blade pitch. Both static and dynamic calibrations of this actuator system have been installed in the computer, which has been programmed for stability and harmonic response testing.

During this reporting period, calibration of the three-channel excitation system has been completed and programmed into the computer. Automated dynamic test programs have been developed which will dynamically excite the rotor model at predetermined conditions and record the desired response data. The purpose of the automated testing procedure is to minimize the duration of forced excitation of the model and thus minimize the potential for fatigue damage. In addition the automated testing includes preprogrammed recording of response data which is time referenced to the blade azimuth angle.

It was deemed necessary to install appropriate monitoring systems to insure the safe operation of the facility. Devices have been installed which monitor the temperatures and accelerations of the drive shaft bearings. If these parameters exceed their anticipated range the test program will be automatically stopped and power to the drive shaft will be terminated. In addition to the monitoring of bearing conditions, pairs of microswitches have been installed on each of the hydraulic actuators. The positioning of these switches can be adjusted so that they will be activated if the actuator exceeds predetermined limits of stroke. Their actuation will disrupt the incoming dynamic actuator control signals and cause all actuators to return to a predetermined value of stroke.

Dynamic testing is currently being performed on the ACR (Aeroelastically Conformable Rotor) model. This system is an articulated nine foot diameter four-bladed rotor on loan from NASA Langley. Two types of dynamic tests are being conducted with this model. One test series is directed to determining the forced response characteristics for various combinations of simple harmonic collective, longitudinal and lateral pitch control. Another series of tests is intended to determine the rotor damping characteristics in each of several rotor modes. These data will then be indicative of the rotor stability characteristics.

The HARP (Hughes Advanced Rotor Program) model has been obtained on loan from McDonnell Douglas Helicopter Co. This model is a bearingless eight foot diameter, four-bladed rotor. Significant repairs are being made to the instrumentation of the blades and mechanical adapters are being designed and constructed so that the model can be tested in AeroTech. These tests are scheduled to begin during May of this year.

UPDATED AND NEW COURSE DEVELOPMENT

The updating of courses and the development of new courses that were listed in the contract have been completed. All courses have been taught at least once except for one updated course, Advanced Aeroelasticity II, which is offered on demand, and one new course, Unsteady Aerodynamics. The Unsteady Aerodynamics course was offered during the spring of 1986. A summary of the status of these courses is shown in Table I. The number indicating the students enrolled includes students in all disciplines in the A.E. Graduate Program. A measure of the interest in the Rotorcraft Program is indicated by the enrollment in the Rotorcraft Design course although the number given includes students not supported by the Center.

ACADEMIC PROGRAM DEVELOPMENT

Discipline	Course No.	Title	Updtd	New	Status	Instructor
Aerodynamics	4600*	Computational Aerodyn.		X	Sum. 1984 - 19**;Wtr. '85- 9**	Sankar
					Wtr. '86-13**	Wu/Wang
	6012*	Viscous Flow III		X	Sum. 1983 - 7**;Sum. '84-20**	Lekoudis/
					Sum. 1985 - 11**	Strahle
	6022	Adv. Compress. Flow II	X		Spr. 1983 - 9**;Spr. '85-11**	Lekoudis
					Spr. 1984 - 13**;Spr. '86-22**	Sankar
	6402*	Aerody. of Helicop.III		X	Sum. 1984 - 8**;Sum. '85-11**	Gray
					Sum. 1986 - 10**	
	6802*	Num.Fluid Dyn.III		X	Fall 1983 - 11**;Fall '85-12**	Wu
	6810*	Unsteady Aerodynamics		X	Spr. 1986 - 22**	Wu
Aeroelasticity	6030	Adv. Potent. Flow I	X		Fall 1982 - 20**;Fall '83-17**	Pierce
					Fall 1984 - 28**;Fall '85-26**	Pierce
					Fall 1986 - 19**	
	6031	Adv. Potent. Flow II	X		Wtr. 1983 - 17**;Wtr. '84-19**	Pierce
					Wtr. 1985 - 21**;Wtr. '86-21**	Pierce
	6200	Adv. Aeroelasticity I	X		Spr. 1983 - 8**;Spr. '84-11**	Pierce
					Spr. 1985 - 11**;Spr. '86- 6**	Pierce
	6201	Adv. Aeroelasticity II	X		Offered on demand	Pierce
	6202	Exp. Aeroelasticity	X		Sum. 1983 - 7**;Sum. '84- 7**	Pierce
	8103	Helicopter Dynamics		X	Win. 1986 - 12**	Peters
Design	6350*	Rotorcraft Design I		X	Spr. 1984 - 13**;Wtr. '85- 9**	Schrage
					Wtr. '86-14**	Schrage
					Wtr. '87-12**	
	6351*	Rotorcraft Design II		X	Sum. 1984 - 7**;Spr. '85-12**	Schrage
					Spr. '86-14**	
					Spr. '87-12**	

*Proposed Course No.

** No. of Students Enrolled

Table I

ACADEMIC PROGRAM DEVELOPMENT(continued)

Discipline	Course No.	Title	Updtd	New	Status	Instructor
Structures	4115*	Intro. Fiber Reinforced Composites		X	Fall 1984 - 20**;Fall '85- 9** Fall 1986 - 9**	Rehfield
	4116*	Manuf. Compos. Struct.		X	Wtr. 1985 - 23** Wtr. 1986 - 20**	Rehfield Rehfield
	6106*	Finite Def. A/C Struct.		X	Sum. 1985 - 10**	Hanagud
	6132*	Vib. Meas. & Analysis		X	Sum. 1984 - 15**	Craig/Hanagud
	6113*	System Identification		X	Sum. 1984 - 10** Sum. 1986 - 13**	Hanagud

*Proposed Course No.

** No. of Students Enrolled

Table I (cont)

**CENTER OF EXCELLENCE
FOR
ROTARY WING AIRCRAFT TECHNOLOGY**

**EXISTING COURSES
ENROLLMENT**

AE 4400 Introduction to Propeller and Rotor Theory

Summer of 1982:	5 Graduate Students 10 Undergraduate Students
Fall of 1982:	8 Graduate Students 14 Undergraduate Students
Summer of 1983:	1 Graduate Student 6 Undergraduate Students
Fall of 1983:	9 Graduate Students 8 Undergraduate Students
Summer of 1984:	1 Graduate Student 5 Undergraduate Students 1 Special Student
Fall of 1984:	17 Graduate Students 22 Undergraduate Students
Summer of 1985:	3 Graduate Students 13 Undergraduate Students
Fall of 1985:	8 Graduate Students 15 Undergraduate Students
Summer of 1986	3 Graduate Students 12 Undergraduate Students
Fall of 1986	7 Graduate Students 14 Undergraduate Students

AE 6400 Rotor Aerodynamics I

Winter of 1983:	13 Graduate Students 3 Undergraduate Students
Winter of 1984:	7 Graduate Students 1 Undergraduate Student
Winter of 1985:	14 Graduate Students
Winter of 1986:	16 Graduate Students

AE 6401 Introduction to Helicopter Stability and Control

Spring of 1983:	10 Graduate Students 1 Undergraduate Student
Spring of 1984:	4 Graduate Students 1 Undergraduate Student
Spring of 1985:	14 Graduate Students
Spring of 1986:	16 Graduate Students

Table II

The rotor theory courses that were in existence when the Center was established continue to be taught. A summary of the enrollments is also attached as Table II. Again, the number of graduate students indicates the interest in the Rotorcraft Program and includes students who are self supported and supported by other means. The Introduction to Propeller and Rotor Theory course attracts a good number of undergraduate students, some of which interview and accept with the helicopter companies.

VISITS/COMMUNICATIONS

1. D. P. Schrage

   U. S. Army Missile Command, Huntsville, AL, July 1, 1986
   Bell Helicopter Textron, Ft. Worth, TX, August 4-6, 1986
   U. S. Army Aviation Applied Technology Directorate, Ft. Eustis, VA, September 24-25, 1986
   AIAA/AHS/ASEE Aircraft Systems, Design & Technology Meeting, Dayton, OH, October 20-22, 1986
   AHS National Specialists' Meeting on Air to Air, St. Louis, MO, October 27-30, 1986
   US Army Research Office, Research Triangle Park, NC, November 17, 1986

2. S. A. Meyer

   American Helicopter Society, Alexandria, VA, August 13-14, 1986
   American Helicopter Society, Alexandria, VA, October 5-6, 1986

3. N. M. Komerath

   United Technologies Research Center, Hartford, CT, September 9, 1986

4. J. C. Wu

   NASA Ames Research Center, Moffett Field, CA, September 7-15, 1986
   United Technologies Research Center, Hartford, CT, September 17-19, 1986

5. L. N. Sankar

   NASA Ames Research Center, Moffett Field, CA, October 5-7, 1986

6. S. V. Hanagud

European Rotorcraft Forum, Garmisch, W. Germany, September 19-October 3, 1986
Bell Helicopter Textron, Ft. Worth, TX, October 20, 1986
US Army Aviation Center, Ft. Rucker, AL, November 19, 1986
US Army Aerostructures Directorate, Hampton, VA, November 20-22, 1986
US Army Aerostructures Directorate, Hampton, VA, December 2-4, 1986
US Army Research Office, Research Triangle Park, NC, December 16, 1986

7. L. W. Rehfield

US Army Research Office, Research Triangle Park, NC, August 25-26, 1986
Rensselaer Polytechnic Institute, Try, NY, September 9-15, 1986

8. G. A. Pierce

European Rotorcraft Forum, Garmisch, W. Germany, September 18-October 3, 1986

9. D. A. Peters

UH-60 Blackhawk Instrumentation Meeting, USA AVSCOM St. Louis, MO, August 5-11, 1986

SIGNIFICANT EVENTS

Computer Programs

The following helicopter computer codes are operational and are being used in various aspects of the Center's activities:

HESCOMP/VASCOMP	NASA/Boeing Vertol	Rotorcraft Sizing and Performance
C81	ARMY/Bell Helicopter	Comprehensive Helicopter Analysis
FLYRT	Hughes Helicopters	Flight Mechanics
DNAM05	ARMY/Bell Helicopter	Vibration Analysis
SSP1/SSP2	ARMY	Single Rotor Helo Sizing and Performance
GTR	Bell Helicopter	Tilt Rotor Flight Mechanics Program
HOVER	ARMY Structures Lab	CFD Hover Analysis
HESS/FREEMAN	NASA/USARTL Langley	Rotor-Airframe Potential Flow
VASERO	NASA Ames	Coupled potential-boundary layer analysis
DYSCO	Kaman Aerospace	Dynamic System Coupler Code
FLIGHT DYNAMICS MICROCOMPUTER CODES	NSWL/Penn State	Dynamic Behavior of Single Rotor/Tail Rotor
CAMRAD	NASA Ames	Comprehensive Helicopter Analysis
ARMCOP	NASA Ames	Stability and Control Simulation
GTPDP	GT/Bell Helicopter	Conceptual and Preliminary Design Optimization

The 1987 AHS Southeast Region Lichten Award Competition was held on the campus of Georgia Tech on December 10, 1986. A follow-on competition will be held at Ft. Eustis, VA on February 10, 1987.

Student design teams from Georgia Tech captured First, Second and Fourth places in the Third Annual American Helicopter Society/Boeing Vertol Student Design competition. The RFP topic was to design a "Sport Helicopter for Home Construction". The faculty advisor for all three teams was Dr. Daniel P. Schrage.

The Center of Excellence for Rotary Wing Aircraft Technology held the annual Advisory Board Meeting on August 16, 1986. Representatives from industry and government agencies attended with a special guest of Dr. Jay Sculley, Assistant Secretary of the Army for Research, Development and Acquisition.

The three ARO sponsored Centers were featured in a Vertiflite article published in the November-December issue. The effort was coordinated by Georgia Tech with authorship by Dr. Daniel P. Schrage, Dr. Robert Loewy of RPI and Professor Alfred Gessow of University of Maryland.

The faculty of the Center welcomed Dr. Dewey Hodges as a valued new addition to our team. Dr. Hodges comes to Georgia Tech from the US Army Aeroflightdynamics Directorate, Moffett Field, CA.

The Center sponsored a workshop on the Dynamics Systems Coupler (DYSCO) program on the campus of Georgia Tech December 9-10, 1986. The workshop included presentations by Kaman Aerospace Corporation, US Army Aeroflightdynamics Directorate, US Army Aviation Applied Technology Directorate and the Air Force Wright Aeronautical Laboratory. A proposal is being prepared for submittal to these organizations to improve the technology modules in DYSCO.

Presentations

"Overview of the V-22 Osprey Tiltrotor"
Mr. Robert R. Lynn, Senior Vice President of Research and Engineering, Bell Helicopter Textron, August 27, 1986

"Solution Procedure for the Unsteady Three Dimensional Euler and Navier-Stokes Equations Applied to Rotors"
Mr. Brian Wake, Georgia Institute of Technology, October 9, 1986

"Experimental Studies of Rotor/Airframe in Forward Flight"
Mr. Albert Brand, Georgia Institute of Technology, October 21, 1986

"Energy Absorption Behavior of Composite Sine Webs"
P. Sriram and W. Zhou, Georgia Institute of Technology, November 18, 1986

"Tilt-Rotor - Past, Present and Future"
Dr. Jing Yen, Director of Technology, Bell Helicopter Textron, November 20, 1986

"Helicopter Development at the Boeing Vertol Company"
Mr. Euan Hooper, Director of Vehicle Technology, Boeing Vertol Company, November 24, 1986

"Nonlinear Beam Kinematics for Small Strains and Finite Rotations"
Dr. Dewey H. Hodges, Georgia Institute of Technology, December 2, 1986

COMPARISON OF COMPOSITE ROTOR BLADE MODELS: BEAM ANALYSIS AND AN MSC NASTRAN SHELL ELEMENT MODEL

Robert V. Hodges and Mark W. Nixon, Aerospace Engineers
Lawrence W. Rehfield, Professor
Aerostructures Directorate, AVSCOM
Langley Research Center
Hampton, VA 23666

ABSTRACT

An analysis was developed by Rehfield for the structural analysis of composite rotor blades. This coupled beam analysis is judged relatively simple to use when compared to the alternative analysis techniques. The beam analysis was developed for thin wall single cell rotor structure and includes the effects of elastic coupling achievable through unbalanced ply orientation.

The purpose of this paper is to demonstrate the effectiveness of the new composite beam analysis method. This is accomplished by comparing results of the coupled beam analysis to an established baseline analysis technique. The baseline analysis tool is an MSC NASTRAN finite element model built up from anisotropic shell elements. Deformations for three linear static load cases are compared. These loads are centrifugal force at design rotor rpm, applied torque, and lift for an ideal rotor in hover. A 'D-spar' designed to twist under axial loading is the subject of the analysis.

At design rotor rpm the baseline analysis and the coupled beam element analysis indicate 14 and 15 degrees of twist at the spar tip respectively. The finite element model indicates less twist due to rigid boundary conditions and wall thickness considerations. A similar trend is indicated by the applied torque load case. In the applied lift load case, vertical deflections and twist indicated by both analysis methods are essentially the same. Results indicate the beam element analysis is well within engineering accuracy.

The results presented demonstrate that moderate variations in spar twist can be achieved by varying the rotor rotational speed. The analysis also provides a new and convenient approach for obtaining the engineering stiffnesses, EA, GK, EI_f. and EI_c.

COMPOSITE BOX BEAM ANALYSIS: THEORY AND EXPERIMENTS

O.A. Bauchau
Rensselaer Polytechnic Institute
Department of Mechanical Engineering,
Aeronautical Engineering and Mechanics

B.S. Coffenberry
Material Sciences Corporation

L.W. Rehfield
Georgia Institute of Technology
School of Aerospace Engineering

ABSTRACT

Beam theory is widely used as a first approximation in numerous structural applications. When applied to composite beams, the accuracy of beam theory becomes questionable because 1) the shearing and warping deformations become significant as the shearing stiffness of composite laminates is often very low, and 2) several elastic couplings can occur that strongly influence the behavior of composite beams. The torsional behavior of thin-walled composite beams has important implications for aeronautical structures and is deeply modified by the above non-classical effects. This paper presents two comprehensive analysis methodologies for composite beams and describes experimental results obtained from a thin-walled, rectangular cross-sectional beam. The theoretical predictions are found in good agreement with the observed twist and strain distributions. Out-of-plane torsional warping of the cross-section is found to be the key factor for an accurate modeling of the torsional behavior of such structures.

A UNIQUE APPROACH TO AEROELASTIC TESTING OF SCALED ROTORS

G. Alvin Pierce, Professor
Steven S. Klein, Senior Research Engineer

School of Aerospace Engineering
Georgia Institute of Technology

ABSTRACT

In 1982 the U.S. Army Research Office commissioned the Georgia Institute of Technology to design and construct a unique testing facility for the purpose of acquiring a comprehensive data base of aeroelastic response characteristics for scaled model helicopter rotors. This data base could then be used in subsequent correlation studies to establish the validity or deficiencies of available analytical methods for the prediction of structural dynamic and/or unsteady aerodynamic phenomena. This paper presents detailed descriptions of the facility which resulted from this effort, the testing philosophy behind its design and use, and current and future test programs conducted in the facility.

AN INVESTIGATION OF HELICOPTER HIGHER HARMONIC CONTROL USING A DYNAMIC SYSTEMS COUPLER SIMULATION

LTC K.P. Nygren
Ph.D. Thesis
School of Aerospace Engineering
Georgia Institute of Technology

ABSTRACT

A free-flight computer simulation of helicopter Higher Harmonic Control (HHC) is developed by incorporation of an HHC solution procedure in the Dynamic System Coupler (DYSCO) Program. The simulation can model almost any HHC control and identification scheme tested to date. The simulation is correlated with previous experiments and simulations, and the assumptions of the mathematical model are analyzed. Investigations are conducted which compare fixed-gain and adaptive control, local and global systems, and deterministic and stochastic optimal control formulations. The OH-6A helicopter with elastic rotor and fuselage is modeled using unsteady aerodynamics. Five baseline regulators are tested at flight velocities of 80, 100, and 120 knots, and the simulation is verified by comparison with previous efforts. Variations in measurement noise, initial transfer matrix, and number of rotor blades is considered. The model is also manuevered from trimmed flight at 80 knots to trimmed flight at 120 knots using large and small step changes. The results indicate fixed-gain, closed loop control can adequately reduce vibration, though not so effectively as adaptive control, except when initialized with an inappropriate transfer matrix.

STRONG BLADE-VORTEX INTERACTIONS INCLUDING COLLISION

W. Tang and L.N. Sankar

School of Aerospace Engineering
Georgia Institute of Technology

ABSTRACT

The problem of strong blade-vortex interaction including collision is studied using an implicit finite-difference procedure. Two-dimensional unsteady compressible Navier-Stokes equations in strong conservation form are solved for both laminar and turbulent flows. A vortex modeling method is developed, which allows the vortex to deform and break up. Complex phenomena such as the vortex induced separation and the convection of broken vortices inside of the boundary layer are observed during the interaction with collision. Results are presented for the variations of aerodynamic loads and the surface pressure distributions. Flow patterns during the interaction are given as streaklines and vorticity contours. The scheme is validated by a number of steady airfoil calculations, and a comparison of the results for interaction without collision with other numerical solutions. Good agreement is observed.

VTOL OPERATIONAL CONSIDERATIONS AND THEIR IMPACT ON FUTURE MILITARY DESIGN REQUIREMENTS

Dr. Daniel P. Schrage
Mr. Stephen A. Meyer

School of Aerospace Engineering
Georgia Institute of Technology

ABSTRACT

Military requirements for greater air mobility, combined with rapidly expanding technological advances in VTOL related scientific fields have brought military planners and aircraft industry leaders some rather perplexing problems in the selection of future aircraft weapon and transportation systems. The ultimate objective is to select a specification for a future aircraft which will best serve the military operation for which it is planneD. This paper will review some of the more demanding operational considerations for VTOL aircraft and their relationship to design requirements.

VTOL OPERATIONAL CONSIDERATIONS AND THEIR IMPACT ON FUTURE MILITARY DESIGN REQUIREMENTS

Dr. Daniel P. Schrage
Mr. Stephen A. Meyer

School of Aerospace Engineering
Georgia Institute of Technology

ABSTRACT

Military requirements for greater air mobility, combined with rapidly expanding technological advances in VTOL related scientific fields have brought military planners and aircraft industry leaders some rather perplexing problems in the selection of future aircraft weapon and transportation systems. The ultimate objective is to select a specification for a future aircraft which will best serve the military operation for which it is planned. This paper will review some of the more demanding operational considerations for VTOL aircraft and their relationship to design requirements.

ROTORCRAFT PRELIMINARY DESIGN EDUCATION

Dr. Daniel P. Schrage
Mr. Stephen A. Meyer

School of Aerospace Engineering
Georgia Institute of Technology

ABSTRACT

In 1982 Georgia Tech was selected by the U.S. Army as one of three universities to establish centers of excellence in rotary wing aircraft technology. Since rotorcraft are complex aircraft and multidisciplinary in nature the Georgia Tech philosophy was to use a graduate rotorcraft design course to provide a synthesis for the academic curriculum and to introduce the graduate students to the multidisciplinary nature of their research. The two quarter graduate rotorcraft design course has proved to be very effective and has served as a catalyst for establishing a broader graduate program in aerospace systems design. This paper will describe how the graduate rotorcraft design course has been developed and implemented in providing rotorcraft preliminary design education.

ROTOR DESIGN FOR MANEUVER PERFORMANCE

John D. Berry and Dr. D. P. Schrage
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

A method of determining the sensitivity of helicopter maneuver performance to changes in basic rotor design parameters is developed. Maneuver performance is measured by the time required, based on a simplified rotor/helicopter performance model, to perform a series of specified maneuvers. This method identifies parameter values which result in minimum time quickly because of the inherent simplicity of the rotor performance model used. For the specific case studied, this method predicts that the minimum time required is obtained with a low disk loading and a relatively high rotor solidity. The method was developed as part of the winning design effort for the American Helicopter Society student design competition for 1984/1985.

E-16-605

PROGRESS REPORT

1. **ARO PROPOSAL NUMBER**: 19364-EG-RW

2. **PERIOD COVERED BY REPORT**: 1 JANUARY - 30 JUNE 1987

3. **TITLE OF GRANT NUMBER**: A CENTER OF EXCELLENCE FOR ROTARY WING AIRCRAFT TECHNOLOGY

4. **CONTRACT OR GRANT NUMBER**: DAAG29-82-K-0094

5. **NAME OF INSTITUTION**: GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF AEROSPACE ENGINEERING

6. **AUTHOR(S) OF REPORT**: R.B. Gray, D.P. Schrage, J.I. Craig, S.V. Hanagud, S.S. Klein, N.M. Komerath, H.M. McMahon, S.A. Meyer, D.A. Peters, G.A. Pierce, L.N. Sankar, L.W. Rehfield, J.C. Wu

7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES**:

Publications:

1. Rehfield, L.W., and A.R. Atilgan, "A Structural Model for Composite Rotor Blades and Lifting Surfaces," AIAA-87-0769-CP, 28th SDM Conference, Monterey, CA, April 6-8, 1987.

2. Chan, W.S., L.W. Rehfield, and T.K. O'Brien, "Analysis, Prediction and Prevention of Edge Delamination in Rotor System Structures," Proceedings of the 43rd Annual Forum of the American Helicopter Society, St. Louis, MO, May 18-20, 1987.

3. Wake, B.E., "Solutions of the Navier-Stokes Equations Applied to Rotors," Ph.D. Dissertation, Georgia Institute of Technology, April 1987.

4. Wake, B.E. and L.N. Sankar, "Solutions of the Navier-Stokes Equations for the Flow About a Rotor Blade," Proceedings of the American Helicopter Society National Specialists Meeting on Aerodynamics and Aeroacoustics, February 1987.

5. Wake, B.E., L.N. Sankar, and S.Y. Ruo, "An Efficient Procedure for the Numerical Solution of Three-Dimensional Navier-Stokes Equations," AIAA Paper 87-1159, Proceedings of the AIAA 8th Computational Fluid Dynamics Conference, June 1987, pp. 617-625.

6. Komerath, N.M., T.L. Thompson, O.J. Kwon, O.J., and Gray, R.B., "The Velocity Field of a Lifting Rotor Blade in Hover". Accepted for publication in the Journal of Aircraft.

7. Taylor, D.J., "A Method for the Efficient Calculation of Elastic Rotor Blade Dynamic Response in Forward Flight," Ph.D. Thesis Advisor: G.A. Pierce, Georgia Institute of Technology, January 1987.

8. Pierce, G.A., "Dynamic Testing Techniques for Controlled Excitation of Scaled Rotors," 5th International Modal Analysis Conference, London, England, April 1987.

9. Tang, W., and L.N. Sankar, "Strong Blade Vortex Interactions Including Collision," Proceedings of the ASME Fluid Engineering Spring Conference, Cincinnati, OH, June 1987.

10. Wu, J.C., and T.M. Hsu, "The Unsteady Forces and Moments Induced by Blade-Vortex Interactions," Proceedings of AHS Specialists' Meeting on Aerodynamics and Aeroacoustics, Arlington, TX, February 1987.

11. Wu, J.C., "Boundary Element Solution of Viscous Flow Problems," Proceedings of 3rd International Conference on Boundary Element Technology, Rio de Janeiro, Brazil, June 1987.

12. Thompson, T.L., O.J. Kwon, J.L. Kemnitz, N.M. Komerath, and R.B. Gray, "Tip Vortex Core Measurements on a Hovering Model Rotor". AIAA Paper 87-0209, 25th Aerospace Sciences Meeting, Reno, NV, January 1987.

Presentations:

1. Rehfield, L.W., "An Overview of Composite Rotor System Research," The Ohio State University, Columbus, OH, January 14, 1987.

2-3. Rehfield, L.W., "Structural Technology for Elastic Tailoring of Rotor Blades":

- University of Texas, Arlington, TX, March 3, 1987
- Bell Helicopter Textron, Inc., Ft. Worth, TX, March 4, 1987

4. Rehfield, L.W., "New Developments in Composite Rotor System Structures," University of California, Davis, CA, May 21, 1987.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Co-Principal Investigators: R.B. Gray and D.P. Schrage

Faculty: R.B. Gray, D.P. Schrage, J.I. Craig, S.V. Hanagud, N. Komerath, H.M. McMahon, D.A. Peters, G.A. Pierce, L.W. Rehfield, N.L. Sankar, & J.C. Wu

Research Engineers: S.S. Klein, R. Latham, S.A. Meyer, M. Meyyappa, and W. Tang

Research Associates: J. Caudell and H. Meyer

Post Doctors: V.R. Anand, T.M. Hsu, and C. Wang

Fellows: Ph.D.: Albert G. Brand, M.W. Heiges, Dimitris N. Mavris, Dana J. Taylor, Brian Wake, and Mark E. Wasikowski

Graduate Research Assistants: Ph.D.: R. Chander, M. Hashemi-Kia, C. He, V.M. Kaladi, Y.K. Kim, O.J. Kwon, S.G. Liou, M.T. Patterson, S. Sarkar, P. Sriram, I. Tuncer, C.C. Won, Y.K. Yillicki, and W. Zhou

Graduate Research Assistants: M.S.: B. Glass, R. Kisor, L.S. Mayer, H.E. Mersinoglou, and R. Srivastava

CONTRIBUTED TO PROJECT BUT WERE NOT SUPPORTED

Faculty: A.J. Calise, D.H. Hodges, and P.K.A. Menon

Research Engineer: V.R.P. Jonnalagadda

M.S. Students: W.P. Crisler and O. Schreiber

DEGREES AWARDED (THIS REPORTING PERIOD)

NAME	DEGREE-DATE	LAST KNOWN AFFILIATION
Jerry W. Anders	MS - June 1987	Lockheed-Georgia
A.R. Atilgan	MS - June 1987	Georgia Tech
Gilbert E. Boen	MS - March 1987	USA AVSCOM
Y.P. Cheng	PhD - March 1987	Georgia Tech
William P. Crisler	MS - June 1987	U.S. Air Force
M.S. Huang	MS - June 1987	Georgia Tech
Steve S. Klein	MS - March 1987	Georgia Tech
Carina M. Tan	MS - March 1987	NASA Ames
D.J. Taylor	PhD - March 1987	USA AVSCOM
B.E. Wake	PhD - March 1987	United Technologies Research Center

DEGREES AWARDED (CUMULATIVE)

NAME	DEGREE-DATE	LAST KNOWN AFFILIATION
V.R. Anand	PhD- Dec 1982	Georgia Tech
Jerry W. Anders	MS - June 1987	Lockheed-Georgia
A.R. Atilgan	MS - June 1987	Georgia Tech
Gilbert E. Boen	MS - March 1987	USA AVSCOM
A.G. Brand	MS - Sept 1985	PhD Program Georgia
T. Boyd	MS - Sept 1983	US Air Force
C. Boyette	MS - Dec 1983	McDonnell Douglas HC
C. Brevoort	MS - Sept 1983	Lockheed Georgia

CPT C.N. Cardinal	MS - June 1984	US Army
H.P. Chen	PhD- Dec 1983	Georgia Tech
Y.P. Cheng	PhD- March 1987	Georgia Tech
MAJ M. Clifford	MS - Dec 1982	US Army
J.E. Corban	BAE- June 1983	McDonnell Douglas HC
	MS - Sept 1986	PhD Program Georgia Tech
William P. Crisler	MS - June 1987	U.S. Air Force
W.K. Daniel	MS - Dec 1986	Vought Corporation
P.L. Elliot, III	BAE- June 1983	Boeing Vertol Co.
K. Engelhardt	MS - Sept 1983	McDonnell Douglas
C. Fouts	MS - Sept 1986	General Dynamics
P.J. Georges	MS - Sept 1984	
C. Grimmell	MS - June 1984	General Dynamics
B.A. Gustavson	MS - Sept 1982	Kaman Aerospace
J.W. Harding	MS - Sept 1986	McDonnell Douglas HC
M. Hashemi-Kia	MS -	PhD Program Georgia Tech
MAJ W.J. Hatch	MS - June 1984	US Army
M.W. Heiges	MS - Sept 1986	PhD Program Georgia Tech
M.S. Huang	MS - June 1987	Georgia Tech
J.A. Humphries	MS - June 1984	US Air Force
A. Izadpanah	PhD- Dec 1986	NASA Langley
R. Jolly	MS - Sept 1986	
V.R.P. Jonnalagadda	MS - Sept 1983	
	PhD- Sept 1985	Georgia Tech
V.M. Kaladi	MS - Sept 1985	PhD Program Georgia Tech
J.L. Kemnitz	MS - Sept 1986	Honeywell Inc., Minneapolis, MN.
Y.K. Kim	MS - Sept 1985	PhD Program Georgia Tech
S.S. Klein	MS - March 1987	Georgia Tech
S.G. Liou	MS - Sept 1985	PhD Program Georgia Tech
L.S. Mayer	MS - Dec 1986	
D. Mavris	MS - Sept 1985	PhD Program Georgia Tech
CPT W. McArthur	MS - March 1983	US Army
LTC K.P. Nygren	PhD- Dec 1986	USMA Faculty
P. Oliver	MS - June 1985	McDonnell Douglas HC
D. O'Neil	MS - Sept 1984	McDonnell Douglas HC
T. Parham	MS - Sept 1983	Bell Helicopter Textron
M.T. Patterson	MS - Sept 1986	PhD Program Georgia Tech
M. Pollack	BAE- June 1986	MS Program Georgia Tech Graduate Co-op Sikorsky Aircraft
G. Power	MS - Sept 1983	United Technologies Research Center
D. Pritchard	MS - Sept 1984	PhD Program Georgia Tech Graduate Co-op McDonnell Douglas HC
J. Rogers	MS - Sept 1983	General Dynamics
O. Schreiber	MS - Sept 1986	PhD Program Georgia Tech
S. Sparks	MS - Sept 1983	United Technologies Research Center
R. Srivastava	MS - Dec 1986	
Carina M. Tan	MS - March 1987	NASA Ames
D.J. Taylor	MS - Sept 1984	
	PhD- March 1987	USA AVSCOM

T. Thompson	MS - Sept 1983	
	PhD- Dec 1986	McDonnell Douglas HC
R.R. Tipton	MS - Aug 1983	McDonnell Douglas HC
B. Wake	MS - Sept 1984	
	PhD- March 1987	United Technologies Research Center
M.E. Wasikowski	MS - Sept 1986	PhD Program Georgia Tech
T. Wey	PhD- Dec 1983	Lockheed-EMSCO, Inc.

RESEARCH TASKS

I. Aerodynamics

Task 1. Experimental Studies for Tip Vortex Core Modeling
N.M. Komerath, R.B. Gray, and O. Kwon

The objectives of this task are to develop a capability for measuring the flow field near the tip and in the wake of a hovering helicopter model rotor using a laser velocimeter and to use the data to guide the development of a tip vortex core model for use in free wake analyses for blade loading predictions.

During this reporting period, analysis of vortex data was continued. It is now reasonably certain that the "scatter" which was previously observed in the vortex core velocity profiles is not due to any measurement inconsistency or jitter effects. Instead, what have been observed are the detailed and complex structure of the inner vortex core of the rotor tip vortex. The vortex is definitely asymmetric, as distinct from fixed wing vortices. The velocity profile inside the core is not monotonic along the radius, and deviates significantly from the usually assumed models.

The database is being organized into report form, and analyzed in greater detail. Tom Thompson at McDonnell-Douglas Helicopters is continuing to collaborate in this effort. During the previous year, Kemnitz and Komerath developed an algorithm to take measured particle velocities and sizes and use these to iteratively arrive at the true fluid velocity field. This was demonstrated for the case of a source in a uniform stream. At present, this work is being extended to the case of a vortex in a uniform stream. Analysis of core data to date have not succeeded in establishing conclusively whether particle lag errors are significant. A Mie scattering analysis routine is being developed as part of an undergraduate student project to attempt particle size measurement by intensity ratioing.

An image digitizing PC board has been ordered and work is being started to attempt automatic location of vortex trajectories from the flow visualization video data base acquired both in hover under Task 1 and in forward flight in Task 5. This is a first step towards development of planar velocity imaging techniques.

One publication has been submitted to the Journal of Aircraft. Both reviews were favorable, and the paper has been tentatively accepted. The revised version has been sent to the editor. A second paper, on the vortex data, is in preparation. Blade tip data acquired under this task have been used by Wake and Sankar for qualitative comparison with their Navier-Stokes code. An abstract (being sent under separate cover) has been submitted to the AIAA Aerospace Sciences Meeting on comparison of vortex data with Professor Sankar's code.

Task 2. Modification of Blade Tip Loading to Improve Hovering Figure of Merit
R.B. Gray

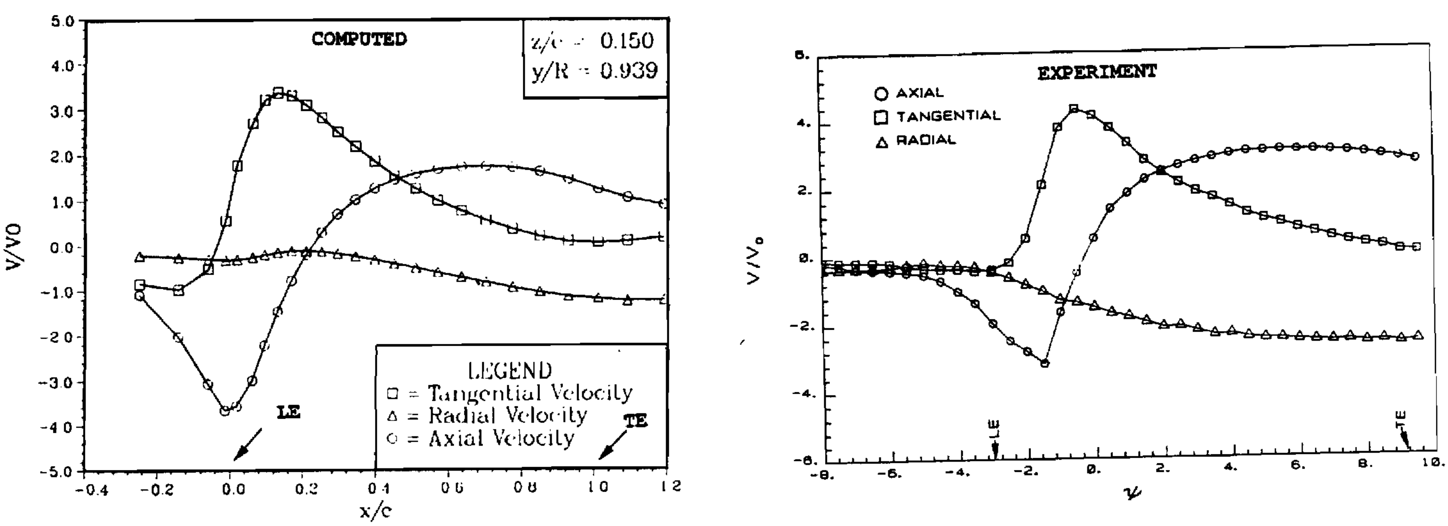
This research task has been completed.

Task 3. Prediction of Flow Around Blade Tips
L.N. Sankar, R.B. Gray, W. Tang, and B.E. Wake

The objective of this task is to develop a procedure to accurately predict the flow field and hence the airloads in the vicinity of the tip of a rotor blade. This requires an accurate modeling of the vortex formation, and roll up processes, and capture of the strength and location of embedded shock waves.

During the reporting period, techniques for improving the efficiency of the 3-D compressible Navier-Stokes solver continued. One of the candidates considered was an iterative time marching algorithm, in which a very large time step is used, and the solution at a given time step is improved iteratively using a Newton-Raphson iterative technique. These studies were carried out using the 2-D counterpart of this 3-D code in order to keep the computer resource requirements small. It was found that this iterative technique improves the time accuracy of the solution, and leads to convergence of the solution to very high levels of tolerance at a given time step. However, the advantages of large time step were offset by the need for more iterations at a given time step, so that no overall improvements to the CPU time requirements was possible.

The Ph.D. thesis work of B.E. Wake was completed. As part of this work, detailed comparisons were done of the predicted velocity field with the LDV measurements made under Aerodynamics Task 1. Good correlation was observed. In Figure 1, sample velocity correlations are shown.



Task 4. Studies of Unsteady Rotor Aerodynamics
J.C. Wu, L.N. Sankar, M. Patterson, R. Srivastava, I. Tuncer

The objective of this task is to develop theoretical and computational tools for the prediction of the unsteady airloads on modern rotor blades in hover and in forward flight.

The development and calibration of the 2-D incompressible and compressible Navier-Stokes solvers have been completed. Support was provided to industry and government lab users who are using these codes, or modifying them for their particular needs. Specifically, the following support was provided.

1. Steve Podleski of Bell Helicopters has modified the 2-D compressible code to handle situations where the airfoil undergoes simultaneous pitching, plunging and lunging motion. The present researchers identified the segments of the code that require changes, and assisted in the calibration of the modified codes.

2. Researchers at NASA Lewis Research Center (Mr. Dennis Huff and Dr. Reddy: contacts) are using the 2-D code to evaluate the static and dynamic load characteristics of thin airfoils used in propfan blades. Support was provided to these researchers in implementing periodic boundary conditions (to simulate the cascade effects). Modifications to the code for improving shock resolution were also made.

3. A videotape of the dynamic stall process as simulated by the 2-D compressible Navier-Stokes code was made with the assistance of researchers at NASA Lewis, and the tape was made available to Dr. Larry Carr, who has explored the same problem using experimental techniques. Dr. Carr and his co-workers will be using this code to study the effects of shock formation on the dynamic stall process.

4. NASA Lewis Research Center has given a grant to the present researchers for the incorporation of the k-ε turbulence model into the 2-D Navier-Stokes code.

Task 5. Studies of the Airframe Flowfield in Forward Flight
H.M. McMahon, N.M. Komerath, A. Brand, D. Mavris, S.G. Liou, R. Kisor

The long-term objective of this task is the development and validation of a reliable technique for predicting the coupling between rotor and airframe aerodynamics. The short term goals are to provide a data base for developing and assessing analytical models, to assess existing analytical models, and to investigate the flow features important in rotor-airframe aerodynamics.

There are several accomplishments to report for this period. A large data base has been compiled using the LDV. Flow visualization data have been used for various interpretive purposes. A new blade has been built and balanced. Computational work has been correlated with experiments and is progressing well. Several publications are being prepared.

a) Flow visualization and interpretation:

The laser sheet flow visualization technique was used to obtain tip vortex trajectories as a function of rotor blade azimuth. These have been correlated with both mean and unsteady airframe surface pressure measurements, and various flow features have been clearly identified. Results from the pressure measurement work have been submitted to the AIAA Journal.

The ability to precisely determine tip vortex positions has been used to guide LDV measurements of the vortex core close to the airframe surface. Measurements of the core radius and velocity profiles through the core have been performed. While lacking the detail of the hover vortex measurements of Task 1, these measurements are an aid in interpreting the surface pressure data. In addition, the axial velocity component in the vortex core has been measured, and has been shown to be much larger than that measured in hover under Task 1. This is to be expected, since there is an azimuthal variation of vortex strength, leading to an axial gradient in the trailing vortex.

b) Measurements with the new blade:

A new blade with a tapered tip has been received. This blade is to be used to obtain an interaction test case with a different rotor load distribution. Dynamic balancing of this rotor has been completed, and preliminary airframe surface pressure measurements indicate a substantially difference from that for the rectangular-planform rotor.

c) Velocity Measurements:

An extensive database has been acquired of both the inflow and outflow at the rotor disk in forward flight, and of the flowfield above the airframe using the laser velocimeter. Rotor outflow measurements (streamwise and downward components) with and without the airframe present were completed along equally-spaced radial and azimuthal positions in a plane 1/2 inch below the rotor disc. Inflow measurements are made at some interesting positions 1/2 inch above the rotor disc. The results show that the presence of the body itself does not have a large effect on the rotor flowfield; however, the presence of the separation region downstream of the hub and mast do cause significant effects. In addition, the presence of the body distorts the vortex trajectories in its vicinity. Variations with advance ratio and body position were investigated to a limited extent. A mirror installed in the tunnel was used to measure the third component of velocity at stations inside the tip vortex when it came close to the airframe. These revealed the result stated above that the vortex core axial velocity is of the same order as the swirl velocity.

d) Analysis:

The Scully code has been modified to include features necessary for interaction with the modified VSAERO airframe code. An interaction algorithm has been devised that uses the experimental result stated above, that body effects on rotor inflow are negligible to first order. The rotor flowfield computations have been automated, resulting in large savings in run time. Also, velocity field computation capabilities have been greatly improved. The code has been validated using inflow data from the recent NASA Langley LDV tests. The conclusion regarding hub effects stated above has been clearly demonstrated by comparison of predicted results with the data sets from Langley (mast below rotor) and our own

LDV data (mast above rotor). Disagreement between the Langley data and published analytical results downstream of the hub have been shown to be due to hub separation effects. Close comparison of predicted and measured data continues. Features added to the codes include the capability to predict velocities at arbitrary points, co-ordinate shifts, changes in the vortex model, and the capability to obtain time-averaged data from the predictions.

e) Wake-body-lifting surface test case:

A NACA 0018 low-aspect-ratio wing is being fabricated. It will be instrumented with pressure ports and is capable of being set at various angles of attack at several positions on the airframe. This will be used to obtain test cases of interactions including lifting surfaces.

One paper on the pressure measurements has been submitted to the AIAA Journal. A technical note on the flow visualization is in preparation. A full paper on the LDV measurements is in preparation. Two abstracts have been submitted to the Aerospace Sciences Meeting at Reno on the flow visualization and LDV measurements.

II. Structures

Task 1. Structural Dynamic System Identification

S.V. Hanagud, J.I. Craig, M. Meyyappa, S. Sarkar, Y. Yillicki

The objective of this task is to develop techniques to effectively identify structural dynamic models that realistically and accurately describe physical structural systems. The research has concentrated on both measurement and analysis methods and has considered the effects of simple nonlinearities, nonproportional damping and large concentrated masses. The most recent work has been directed at the problem of rotor blade system identification with particular interest in the damping characteristics and the uniqueness of the identification. The current work is concerned primarily with fundamental techniques for identification of distributed parameter models that uniquely describe physical systems.

Identification Techniques

Frequency domain identification techniques are being developed for linear distributed parameter systems. These techniques can be applied to estimate the unknown coefficients appearing in the partial differential equations describing certain structural systems, beams and plates for example, that are modeled by such equations. By avoiding the customary approach in which the structure is first discretized and later identified as a finite degree of freedom system, any loss of accuracy due to discretization is minimized so the identified model may lead to more accurate predictions of the system response.

The formulation involves transforming the partial differential equations into the frequency domain, resulting in a reduction to ordinary differential equations that are largely linear in the unknown parameters. In order to illustrate the procedure, the problem of identifying the varying parameters of a beam is being considered. Techniques developed for this case can be employed to determine the structural properties of systems such as helicopter rotor blades. An equation error or collocation approach is being adopted in which the ODE describing the beam in the frequency domain is evaluated at a number of points along the length and the unknown parameters are estimated so that the error in satisfying the equation at these locations is minimized. The spatial displacement derivatives are computed from a quintic B-spline representation of the response which is constructed using the available discrete response measurements. The derivatives of unknown parameters are expressed in terms of the parameters themselves by utilizing cubic spline forms which leads to a system of equations in which the only unknowns are the parameter values at all the locations used in the identification. Repeating the procedure with measured data at many different frequencies yields an over-determined set of equations that is solved for the parameters.

Preliminary results using this technique appear encouraging. Parameters have been estimated with input-output data generated for two types of spatial loading including point and uniformly distributed loads, both of which are assumed to be impulsive in the time domain. Satisfactory results have been obtained with uniformly distributed loads for the stiffness and damping coefficients of the beam assuming that the mass is known. The procedure yields unacceptable estimates for the damping parameters in the case of a point load. An alternative approach is being considered in which the equations are obtained by a weighted residual method rather than through collocation at various points on the beam. The weighting functions are chosen to be the linearly independent basis functions used in the parameter spline representations.

Measurement Techniques

The work on measurement techniques has concentrated on the problem of testing structures with large fixed masses and complex geometries such as rotorcraft structures. The development of physically realizable reduced order models and the interpretation and accommodation of nonlinearities and errors in the vibration measurement process have been the focus of the research. The methods developed for single input, multiple output testing are now being extended to multiple input testing conditions.

Task 2. Crashworthy Characteristics of Composite Rotorcraft Structures

S.V. Hanagud, J.I. Craig, R. Chander, P. Sriram, C.C. Won, and W. Zhou

The objective of this task is to conduct basic research to develop improved techniques and procedures for designing crashworthy composite structures for rotorcraft. This includes the development of analysis methods, testing techniques, and crashworthy design optimization under constraints of weight, cost and performance.

Crashworthiness Testing

Fabrication: The fabrication of a failure initiator poses problems in the case of the sine webs. Ply drop-off is somewhat difficult to control in the absence of mechanized lay up, and chamfering involves difficult machining operations. A notching scheme has been developed that allows the web to be connected to flange-like end members while retaining highly repeatable failure initiation. Static crushing tests have been conducted on various widths and relative notch and geometric side conditions. The results have shown that lateral (unloaded) boundary effects are minimal, and thus the web structure can be modelled as single wave elements.

Dynamic Testing: The dynamic drop-test facility has undergone modifications to remedy problems and improve performance accuracy. The force and stroke measuring subsystems have been exhaustively studied, are well understood, and are performing properly. Dynamic tests with graphite-epoxy sine web specimens have been performed and the results agree qualitatively with the static test results in terms of failure modes, peak and average loads, and stroke characteristics.

Failure Mechanisms

In order to establish the failure modes of the initiated failures in sine-web specimens, the failure zones were examined with an SEM. The specimens exhibit a crack propagating slightly ahead of the total (fragmentation) failure approximately at the mid-plane of the section. This crack is not a simple delamination type failure but involves transverse fiber cracking also. This view is further supported by the fragmentation of the specimen observed as the failure zone progresses through it. This area of research is providing significant new information about the crushing behavior and is expected to form the basis for more accurate failure models.

Task 3. Concepts for Stability Critical Airframe Structures
L.W. Rehfield

Postbuckled Airframe Structure

This task is concerned with crippling and postcrippling behavior of thin walled graphite/epoxy composite airframe members in axial compression. The main objectives are to i) generate an experimental data base on the crippling and postcrippling behavior, ii) develop simple analytical methods to predict these behavior, and iii) provide better insight into the failure processes for this type of structure.

This research is approaching the point of fundamentally new results in understanding the behavior of postbuckled elements and their failure processes (crippling). The ability to reliably predict events is near at hand. Emphasis is being given to areas where gaps exist in our knowledge and in the technology base.

Experiments have been conducted to determine the mean axial strain distribution in postbuckled flanges, the one-edge-free elements of our I-beam specimens. The experimental results confirm our theoretical predictions that the mean strain remains nearly uniform across the flange width and does not appreciably increase with increased shortening. As a result, a simple model for postbuckled flanges is simply to consider them carrying only the constant buckling load in the postbuckled region.

This is a keystone to our analytical design methodology.

Discrepancies between theory and experiment exist for ply layups with [45] plies. Currently, additional experiments are being performed to clarify this situation.

Composite Rotor Blade Modeling

The composite rotor blade theory is in an advanced state. Three items have been emphasized during this period. The first is preparing previous accomplishments for publication. We are writing on three manuscripts.

The second is an exploratory study on the influence of bending-twisting coupling on blade response. The results are interesting and suggest further study would be fruitful.

The third is a correlation study which is concerned with coupled tube vibration experiments conducted by Mark Nixon at the USA Aerostructures Directorate. A NASTRAN analytical simulation was performed by Renee Lake. We are interested in whether a very simple beam model will correlate. Results to date are inconclusive. Additional work is needed.

III. Aeroelasticity

Task 1. Helicopter Vibration Suppression Techniques

G.A. Pierce, V. Anand, V.M. Kaladi, Y.K. Kim, and D.J. Taylor

The overall purpose of this program is to develop and validate comprehensive vibratory loads analyses for the evaluation of vibration suppression techniques. The loads analyses are to be applicable to nonuniform multibladed systems with various hub constraints. Special emphasis is to be placed on blade structural dynamics and unsteady blade aerodynamics.

Dynamic testing has been performed on the ACR (Aeroelastically Conformable Rotor) model. This system is an articulated nine feet diameter four-bladed rotor on loan from NASA Langley. Four types of response tests were conducted with this model. The first was a series of steady pitch control runs at various speeds and combinations of collective, longitudinal and lateral pitch settings. Secondly a series of runs were made with a four-per-rev collective pitch about various mean collective settings and speeds. The third type of testing examined the transient behavior of the rotor system as the four-per-rev collective excitation was abruptly removed again at various mean settings and speeds. The fourth and final type of test consisted of imposing various rapid ramp changes to the collective pitch at different speeds.

The HARP (Hughes Advanced Rotor Program) model was obtained on loan from McDonnell Douglas Helicopter Company (MDHC). This model is a bearingless eight feet diameter four-bladed rotor. Mechanical adapters have been designed and constructed so that the model can be tested in AeroTech. These tests were scheduled to begin during May of this year, but it was necessary to return the rotor system to MDHC. The instrumentation of the blades is being replaced in preparation for a Whirl Test at the Ames facility during June of this year and a subsequent wind tunnel test series at the DNW facility in the Netherlands in September. It is anticipated that the model will be returned to AeroTech for additional dynamic testing during the winter of 1987-1988.

Task 2. Rotorcraft Aeroelastic Active Control Investigations
D.P. Schrage, D.A. Peters, M.E. Wasikowski, V.R.P. Jonnalagadda and C. He

The purpose of the research in this task is to study, evaluate and compare the alternative controller configurations that have been shown either theoretically or experimentally to have the potential for providing favorable aeroelastic response. This research consists of both an analysis and an experimental program.

Research in this task has proceeded along the lines of investigating aeroelastic active control techniques and advancing the dynamic inflow theories for aeroelastic excitation in an efficient, but representative manner.

With respect to active control techniques, the research has moved toward investigating the application of frequency and time domain cost functionals to active vibration control. Optimal regulator algorithms in both the frequency and time domain are formulated utilizing higher harmonic and individual blade control, respectively. The frequency domain approach implements fixed gain, adaptive, cautious and dual regulators with a Kalman filter to identify the parameters of either a local or global static model. The time domain regulator uses a frequency shaped cost functional to minimize narrow band vibration levels at the pilot seat. The applications are applied to the OH-6 dynamic model discussed in the last progress report but now addresses control in the rotating as well as the fixed system.

With respect to dynamic inflow theories, our work has concentrated on their extension to higher harmonics and on comparison with experimental data. Comparisons with the data of Norm Ham at MIT, of Kurt Hohenemser of Washington University, and of Carpenter and Fridovich (circa 1955) have yielded new insights into the detail of dynamic inflow modeling that is necessary for aeroelasticity. In addition, our own data on the Advanced Conformable Rotor (ACR) model, taken in the Aeroelastic Facility at Georgia Tech, has given important information on dynamic inflow behavior at low thrust conditions. All of this work is leading toward innovative improvements in inflow modeling.

A paper discussing some of these results for full state feedback control will be presented at the AHS Specialists Meeting on Advanced Flight Controls and Avionics in Cherry Hall, NJ, in October 1987, while results for output feedback control will be presented at the 2nd US ARO Workshop on Dynamics and Aeroelastic Stability Modeling of Rotor Systems at Florida Atlantic University in November 1987.

FACILITIES/EQUIPMENT

I. Laser Doppler Velocimeter (LDV) Data Acquisition System
N.M. Komerath, H.M. McMahon, and R.B. Gray

The two-component LDV uses a 5-watt Argon Ion laser, modular optics and electronics and a three-axis computerized traverse system. Two orthogonal components of instantaneous flow velocity can be measured simultaneously with a spatial resolution of 0.1 mm from a distance of upto 2200mm. Recirculating flows can be measured. A unique Remote-Aligned Light Collection system developed at Georgia Tech permits precise measurement of vortex flows in large facilities. Software developed in-house enables tailoring of a variety of measurement options.

The LDV has seen extensive use. The near wake of a rotor, blade tip flowfield, and vortex core velocity profiles have been measured in detail in the 9-foot hover facility. The fluctuating flowfield between the rotor and airframe in the Forward Flight facility has been measured. A high-resolution database on the inflow and outflow velocities of a rotor disc in forward flight has been completed. The laser has been used to visualize the detailed dynamics of the vortex-dominated flowfield in both facilities. It has also been used to precisely locate the tip path plane.

II. Nine-Foot Static Thrust Facility

R.B. Gray and N.M. Komerath

This facility provides a laboratory-controlled environment for testing model helicopter rotors up to 4.5 feet in diameter in hovering flight. A high-speed, 16-channel A/D converter and an HP1000 A700 computer system enable thrust, torque, pressure and velocity measurements. This facility has been used for LDV, flow visualization, and some acoustic measurements. New tests on BERP-tip rotors are planned to assist in code development.

III. Structural Dynamic System Identification Facility

S.V. Hanagud and J.I. Craig

This laboratory is developed to measure, record, process, and analyze structural dynamic data for laboratory model tests and field tests. The multichannel time series and structural dynamic analyzer allows acquisition of data from one to eight channels simultaneously with the capability to expand to sixteen. The analysis software may run on the dedicated computer system or is portable to another system.

IV. Transient Dynamic Stress Analysis Facility

S.V. Hanagud and J.I. Craig

This facility is for the study of the dynamic behavior of structural components and assemblies under typical crash-induced loading situations for helicopters. The design of the facility involves a drop-test fixture for producing dynamic compressive loading of various metallic and composite test articles. A variety of waveform recorders acquire data during investigation of crashworthy characteristics of rotorcraft structures, particularly composite structures.

V. Seven-by-Nine Foot Forward Flight Facility

H.M. McMahon and N.M. Komerath

The John J. Harper Low Speed Wind Tunnel serves as a forward flight facility, with a powered rotor and sting- or balance-mounted airframe models. The data acquisition system includes computerized force measurement, mean pressure scanning, four microphone channels, vibration monitors, a 16-channel A/D converter, HP1000 A700 minicomputer, and color video system. The LDV system is used routinely here, as is laser sheet flow visualization. A computerized 3-axis traverse permits rapid surveys using pressure probes or a two-channel hot-wire anemometer. In-house software permits time-series analysis using phase or spectral averaging, dynamic balancing of rotors, and rapid graphical display of results.

VI. Aeroelastic Rotor Test Chamber (AeroTech)
G.A. Pierce, S. Klein, and M. Hashemi-Kia

The primary purpose of AeroTech is to experimentally simulate and record various aeroelastic phenomena associated with contemporary helicopter systems. The information compiled with this facility will form a valuable data base with which to correlate the predictions obtained from newly developed analytical techniques.

This facility has a computer-based data acquisition system which can simultaneously receive, condition, record and analyze up to 48 channels of response parameters. The on-line analysis of these data can be preprogrammed in FORTRAN 77 or processed by a time-series analyzer. The facility also has a three-channel hydraulic excitation system which permits on-line computer control of a swashplate mechanism for the dynamic excitation and control of the model rotor in blade pitch. Both static and dynamic calibrations of this actuator system have been installed in the computer, which has been programmed for stability and harmonic response testing.

UPDATED AND NEW COURSE DEVELOPMENT

The updating of courses and the development of new courses that were listed in the contract have been completed. All courses have been taught at least once except for one updated course, Advanced Aeroelasticity II, which is offered on demand. The rotor theory courses that were in existence when the Center was established continue to be taught. The Introduction to Propeller and Rotor Theory course attracts a good number of undergraduate students, some of which interview and accept with the helicopter companies.

VISITS/COMMUNICATIONS

1. D. P. Schrage

June 22-26, 1987	Bell Helicopter Textron, Ft. Worth, TX, and McDonnell Douglas Helicopter Company, Mesa, AZ

2. S. V. Hanagud

March 4, 1987	USA Aerostructures Directorate, Hampton, VA
April 5-12, 1987	USA Aeroflightdynamics Directorate, Mountain View, CA
May 18-19, 1987	American Helicopter Society Annual Forum, St. Louis, MO

3. S.S. Klein

April 22-23, 1987	U.S. Army Aviation Center, Ft. Rucker, AL
May 17-19, 1987	American Helicopter Society Forum, St. Louis, MO
June 21 - July 1, 1987	USA Aeroffightdynamics Directorate, Mountain View, CA

4. N. M. Komerath

Jan. 10-13, 1987	AIAA 25th Aerospace Sciences Meeting, Reno, NV

5. S. A. Meyer

Feb. 17-19, 1987	USA Missile Command, Huntsville, AL
April 30 - May 8, 1987	Bell Helicopter Textron, Ft. Worth, TX, and NASA Ames Research Center, Mountain View, CA

6. G. A. Pierce

March 26- April 10, 1987	5th International Modal Analysis Conference London, England

7. L. N. Sankar

June 6-12, 1987	AIAA 8th Computational Fluid Dynamics Conference, Waikiki, HI

8. J. C. Wu

Feb. 24-27, 1987	AHS National Specialists' Meeting on Aerodynamics and Aeronautics, Dallas, TX
May 20, 1987	American Helicopter Society Annual Forum, St. Louis, MO

SIGNIFICANT EVENTS

Computer Programs

The following helicopter computer codes are operational and are being used in various aspects of the Center's activities:

HESCOMP/VASCOMP	NASA/Boeing Vertol	Rotorcraft Sizing and Performance
C81	ARMY/Bell Helicopter	Comprehensive Helicopter Analysis
FLYRT	Hughes Helicopters	Flight Mechanics
DNAMO5	ARMY/Bell Helicopter	Vibration Analysis
SSP1/SSP2	ARMY	Single Rotor Helo Sizing and Performance
GTR	Bell Helicopter	Tilt Rotor Flight Mechanics Program
HOVER	ARMY Structures Lab	CFD Hover Analysis

HESS/FREEMAN	NASA/USARTL Langley	Rotor-Airframe Potential Flow
VASERO	NASA Ames	Coupled potential-boundary layer analysis
DYSCO	Kaman Aerospace	Dynamic System Coupler Code
FLIGHT DYNAMICS MICROCOMPUTER CODES	NSWL/Penn State	Dynamic Behavior of Single Rotor/Tail Rotor
CAMRAD	NASA Ames	Comprehensive Helicopter Analysis
ARMCOP	NASA Ames	Stability and Control Simulation
GTPDP	GT/Bell Helicopter	Conceptual and Preliminary Design Optimization

A group of scientists from Cray Research, Inc., visited the present investigators in February 1987, to discuss the use of the 3-D Navier-Stokes code. A copy of the 3-D Navier-Stokes code plus accompanying documentation was made available to them. One of the CRAY researchers, Kent Misegades, has been making independent benchmark studies on the CRAY XMP's located at Mendota Heights, Minnesota.

Mr. Robert R. Lynn, Senior Vice President of Research and Engineering, Bell Helicopter Textron, visited on January 22, 1987, and gave a presentation on "The Tilt-Rotor, Past, Present, and Future.

Researchers at NASA Lewis Research Center (Dr. K.R.V. Kaza, contact) are interested in modifying the 3-D Navier-Stokes code for prop-fan applications, and have provided a research grant (Start Date: April 1987).

Dr. Kip Nygren, a December 1986 Ph.D. graduate now a full time faculty member at the United States Military Academy, won the Southeast Region Lichten Award Competition and was invited to the 43rd Annual American Helicopter Society Forum, St. Louis, Missouri, as a finalist.

Two student design teams have entered the 4th American Helicopter Society National Student Rotorcraft Design Competition. The Request for Proposal outlined "A Low Cost Tiltrotor for Commuter Operations.

The Call for Papers for the American Helicopter Society National Specialists' Meeting on Automation Applications for Rotorcraft which will be held in Atlanta from April 4-6, 1988.

The Atlanta Chapter of the American Helicopter Society, comprised primarily of Center faculty and students, won the "Every Member get a Member" award at the Annual Forum in May 1987.

ANALYSIS, PREDICTION, AND PREVENTION OF EDGE DELAMINATION IN ROTOR SYSTEM STRUCTURES

Wen S. Chan
Bell Helicopter Textron, Inc.
Fort Worth, TX

Larry W. Rehfield
Center for Rotary Wing Aircraft Technology
Georgia Institute of Technology
Atlanta, GA 30332-0150

T. Kevin O'Brien
Aerostructures Directorate
U.S. Army Research and Technology Activity
NASA Langley Research Center
Hampton, VA

Abstract

Analytical methods such as simple sublaminate analysis, as well as quasi three-dimensional finite element analysis, provide insight into delamination characteristics and reliable trend data with which to make rapid evaluations of competitive concepts in the design environment. It is concluded that free edge delamination can be managed by analysis and prevented by design. However, in order to ensure durable composite structures, more work is needed to characterize delamination that occurs from other sources, such as matrix cracking and ply drops.

SOLUTIONS OF THE NAVIER-STOKES EQUATIONS FOR THE FLOW ABOUT A ROTOR BLADE

Brian E. Wake and Lakshmi N. Sankar

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

A numerical solution procedure for solving the three-dimensional unsteady Navier-Stokes equations is described and applied to the flow over a helicopter rotor blade. This procedure solves the Navier-Stokes equations in a time-accurate manner. Steady solutions are obtained by marching through time and asymptotically converging to steady state. The procedure is a hybrid ADI scheme that has previously been applied to the solution of the Euler equations for fixed and rotary wings. The present hybrid procedure results in an efficient method, capable of handling relatively large time steps. The influence of the rotor wake is included by the transpiration-velocity technique. For turbulence, a two-layer algebraic model is used. The method is applied to the subsonic flow of a hovering rotor blade with encouraging results. Unsteady calculations for a high-speed nonlifting rotor have also been made and compared with experimental data and Euler results.

AN EFFICIENT PROCEDURE FOR THE NUMERICAL SOLUTION OF THREE-DIMENSIONAL VISCOUS FLOWS

B.E. Wake, L.N. Sankar, and J. Wu
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

S.Y. Ruo
Lockheed-Georgia Company
Marietta, GA 30063

Abstract

A solution procedure is described for the numerical solution of steady and unsteady compressible viscous flow past wing-alone, and rotor configurations. This procedure solves the three-dimensional unsteady Navier-Stokes equations in a body-fitted coordinate system. A finite difference procedure of second order spatial accuracy and first order temporal accuracy is used to discretize the governing equations, and a hybrid time marching scheme is used to advance the solution from one time level to the next. This procedure lends itself to efficient solution on the current generation vector machines. In unsteady applications involving oscillating wing surfaces or rotating rotor blades, the surface motion is treated exactly, by allowing the body-fitted grid to rotate or deform. Sample steady and unsteady calculations are presented for fixed and rotary wing configurations. Detailed surface pressure and integrated load comparisons with experiments are given.

STRONG BLADE-VORTEX INTERACTIONS INCLUDING COLLISION

W. Tang and L.N. Sankar
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

The problem of strong blade-vortex interaction including collision is studied using an implicit finite-difference procedure. Two-dimensional unsteady compressible Navier-Stokes equations in strong conservation form are solved for both laminar and turbulent flows. A vortex modeling method is developed, which allows the vortex to deform and break up. Complex phenomena such as the vortex induced separation and the convection of broken vortices inside of the boundary layer are observed during the interaction with collision. Results are presented for the variations of aerodynamic loads and the surface pressure distributions. Flow patterns during the interaction are given as streaklines and vorticity contours. The scheme is validated by a number of steady airfoil calculations and a comparison of the results for interaction without collision with other numerical solutions. Good agreement is observed.

Accepted for publication in the Journal of Aircraft

THE VELOCITY FIELD OF A LIFTING ROTOR BLADE IN HOVER

N.M. Komerath, T.L. Thompson, O.J. Kwon, and R.B. Gray
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

Detailed measurements have been made using a laser velocimeter in the close vicinity of a lifting, single-bladed model rotor blade in simulated hover conditions to validate codes for predicting rotorcraft aerodynamics. Data acquired at a rotor tip speed of 32 m/s and tip Reynolds number of 280,000 are compared here with predictions made using a thick-bladed panel code coupled to a prescribed wake calculation. Rotor inflow measurements are seen to agree closely with panel code results, even when examined with high chordwise resolution. Agreement is less definite in the near wake, where strong tip vortex effects are felt, and the vortex core model becomes important. Tip vortex formation is clearly visible from the data. Deviations from periodicity are insignificant in the close vicinity of the blade. Particle spin-out effects are seen to be pronounced in the vortex core when using conventional seeding materials, but to be greatly reduced by the use of incense seeding. The precise measurement of vortex core velocity profiles is seen to be within reach.

DYNAMIC TESTING TECHNIQUES FOR CONTROLLED EXCITATION OF SCALED ROTORS

G. Alvin Pierce, Professor
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

In 1982 the U.S. Army Research Office commissioned the Georgia Institute of Technology to design and construct a unique testing facility for the purpose of acquiring a comprehensive data base of aeroelastic response characteristics for scaled model helicopter rotors. This data base could then be used in subsequent correlation studies to establish the validity or deficiencies of available analytical methods for the prediction of structural dynamic and/or unsteady aerodynamic phenomena. This paper presents detailed descriptions of the facility which resulted from this effort, the testing techniques developed for its use, and current and future test programs conducted in the facility.

A STRUCTURAL MODEL FOR COMPOSITE

ROTOR BLADES AND LIFTING SURFACES*

Lawrence W. Rehfield and Ali R. Atilgan**
Center for Rotary Wing Aircraft Technology
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
(404)894-3067

EXTENDED ABSTRACT

Introduction

Composite material systems are currently primary candidates for aerospace structures. One key reason for this is the design flexibility that they offer. It is possible to tailor the material and manufacturing approach to the application. Two notable examples are the wing of the Grumman/USAF/DARPA X-29 and rotor blades under development by the U.S.A. Aerostructures Directorate (AVSCOM), Langley Research Center.[1]

A working definition of elastic or structural tailoring is the use of structural concept, fiber orientation, ply stacking sequence and a blend of materials to achieve specific performance goals. In the design process, choices of materials and dimensions are made which produce specific response characteristics which permit the selected goals to be achieved. Common choices for tailoring goals are preventing instabilities or vibration resonances or enhancing damage tolerance.

* Sponsored by ARO under Contract DAAS29-82-K-0097 and by USA Aerostructures Directorate under grant NAG1-638.

** Professor, Associate Fellow AIAA and NATO Scholar, respectively.

An essential, enabling factor in the design of tailored composite structures is structural modeling that accurately, but simply, characterizes response. Simplicity is needed as cause-effect relationships between configuration and response must be clearly understood and numerous design iterations are required. The objective of this paper is to improve the single closed-cell beam model previously developed by the senior author[2] for composite rotor blades or lifting surfaces and to demonstrate its usefulness in applications.

Modeling Improvements

Two major improvements have been made in the model of Reference 2. They are:

(1) More accurate representation of twisting deformation; and

(2) Simplification of the representation of torsion-related warping.

Outline of the Present Work

An analysis of the behavior of the model Langley rotor blade under three static load cases appears in Reference 1. The model rotor cross section is shown in Figure 1. The same three loading cases have been considered. The first case is bending due to lift and blade weight, the second is pure torque and the third is axial loading due to centrifugal force.

In Reference 1, a classical version of the theory of Reference 2 is compared with an extensive finite element simulation based upon orthotropic shell elements. Attention is focused upon the small discrepancies in the earlier study which are correctly attributed to torsion-related warping. This confirms the findings reported in Reference 3. Also, an assessment of nonclassical effects in bending behavior has been made.

Bending Due to Lift and Blade Weight

Beam deflection results from the bending case appear in Figure 2. Bernouli-Euler, the classical engineering beam theory, results are denoted by "BE." This model is overly stiff. Also presented are three shear deformation models, SD1, SD2 and SD3, and the finite element results.

The shear deformation model S1 is an approximation obtained by setting the coupling stiffness C_{25} and C_{36} in Reference 2 to zero. This is the classical shear deformation model in the spirit of Timoshenko. Clearly it is overly stiff also. This direct transverse shear effect is small for a beam of this slenderness.

The complete theory, which includes all coupling effects, is denoted SD3. It provides good agreement with the finite element results.

The approximation denoted SD2 is obtained by neglecting completely the classical shear deformation effect accounted for in SD1 in favor of the coupling mechanism associated with C_{25} and C_{36}. This model, therefore, includes only deformations due to the transverse shear-bending coupling and the usual bending contribution. The magnitude of this new, unexplored form of elastic coupling is seen to be enormous by comparing SD2 and BE results. This is a finding of major importance in understanding the behavior.

The SD2 or SD3 models are required in this application in order to get sufficiently accurate predictions. This clearly excludes the earlier classical type theory of Mansfield and Sobey[4] from practical use.

Pure Torque

The classical St. Venant torsion theory result (without warping) is compared to the complete beam theory (CBT) and the finite element results in Figure 3. The CBT results, which differ from the classical (CL) only by the warping effect, are in excellent agreement with the finite element analysis. Restrained warping creates a boundary layer zone near the blade root that acts to stiffen the blade and reduce the angle of twist.

Axial Loading Due to Centrifugal Force

This case is of the utmost importance because extension-twist coupling is to be used to control blade stall, an application of elastic tailoring. The discrepancy between analytical predictions and the finite element analysis was the greatest for this case. Classical theory was too soft and it overestimated the twist angle, a condition that is not conservative in view of the stated purpose of the model demonstration.

As in the pure torsion case, the neglect of torsion-related warping is the reason for the discrepancy between coupled beam theory and the finite element analysis.

The twist angle distribution appears in Figure 4. The use of CBT brings the beam theory results in very good agreement with the finite element analysis. The rate of twist distribution is given in Figure 5. Again, the agreement is very good.

Conclusions

In structures designed for extension-twist coupling, a high degree of bending-shear coupling is present which drastically causes the structure to be more flexible in bending. The impact of this effect on system performance must be assessed.

Torsion-related warping is significant enough to warrant its inclusion in the beam analysis. With warping accounted for, the coupled beam theory is extremely accurate and easy to use.

References

1. Hodges, R.V., Nixon, M.W. and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastran Shell Element Model," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, GA, 4-5 December 1985.

   To be published as a NASA/AVSCOM Technical Memorandum, 1986.

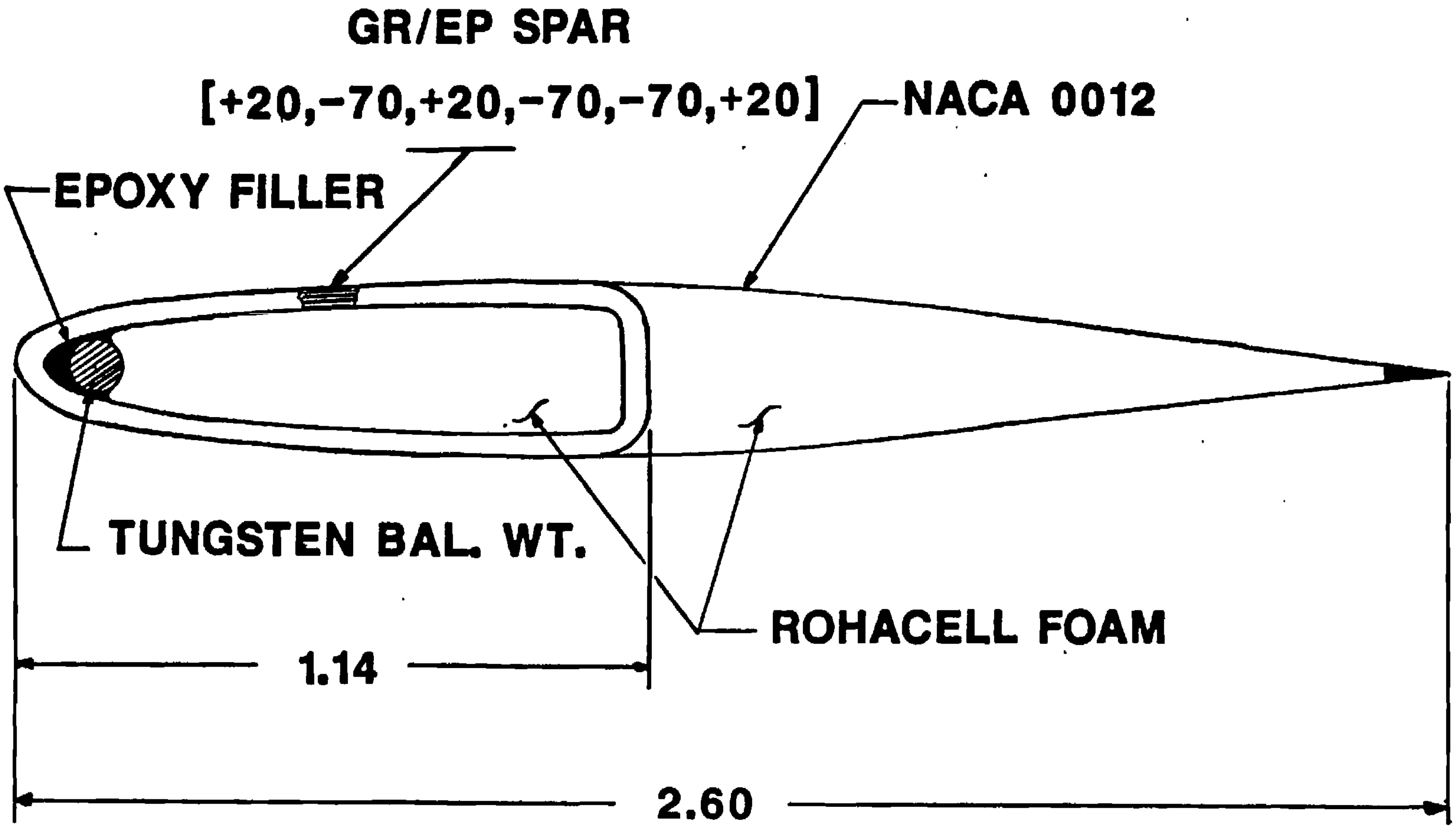
2. Rehfield, L.W., "Design Analysis Methodology for Composite Rotor Blades," Proceedings of the Seventh DoD/NASA Conference on Fibrous Composites in Structural Design, AFWAL-TR-85-3094, June 1985, pp.(V(a)-1)-(V(a)-15).

3. Bauchau, O., Coffenberry, B.S. and Rehfield, L.W., "Composite Box Beam Analysis: Theory and Experiments," to appear in the January 1987 issue of the Journal of Reinforced Plastics and Composites.

4. Mansfield, E.H. and Sobey, A.J., "The Fibre Composite Helicopter Blade, Part 1: Stiffness Properties, Part 2: Prospect for Aeroelastic Tailoring," Aeronautical Quarterly, May 1979, pp. 413-449.

FIG. 1

MODEL ROTOR CROSS SECTION



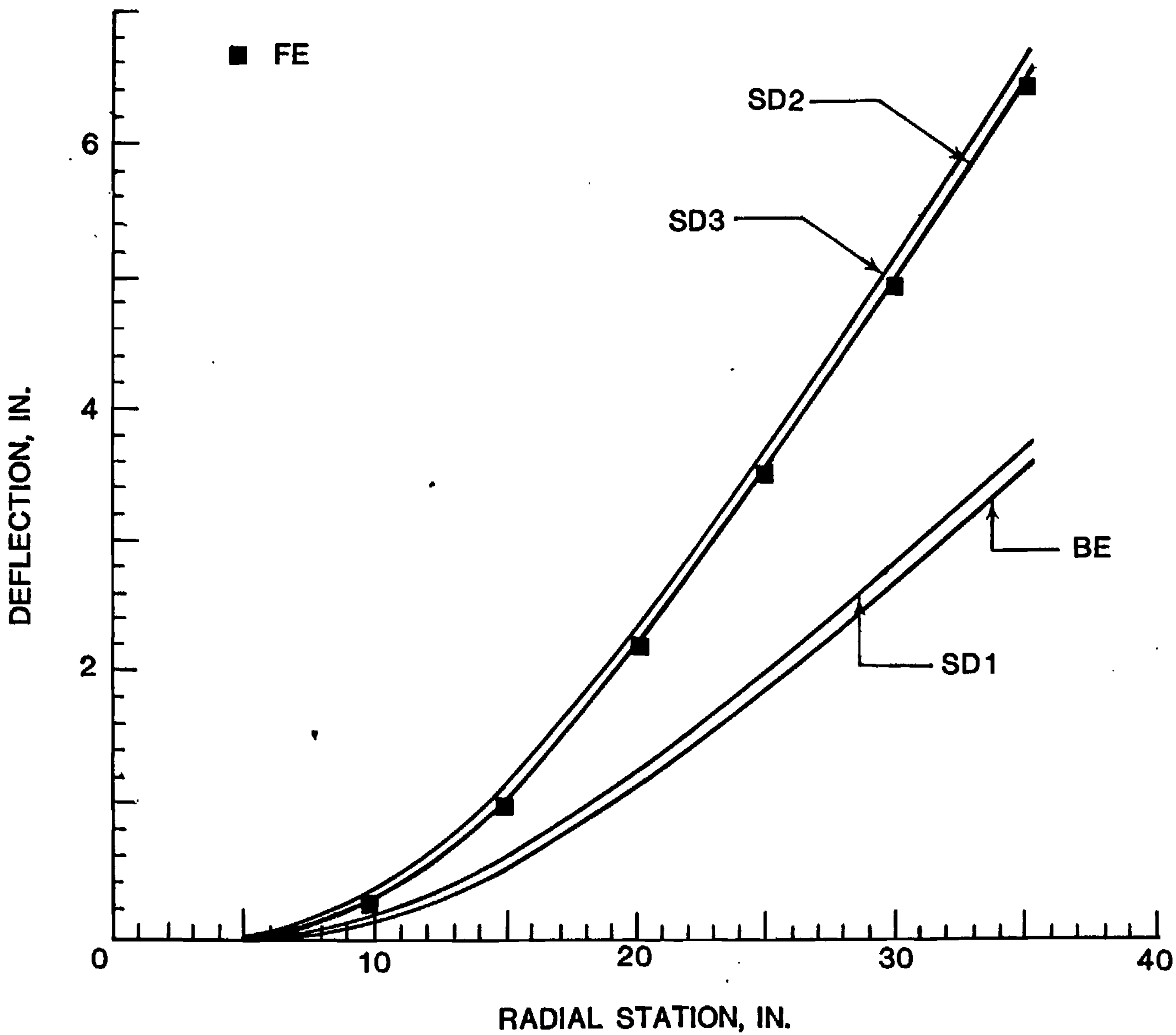


FIGURE 2

BEAM DEFLECTION DUE TO LIFT AND BLADE WEIGHT

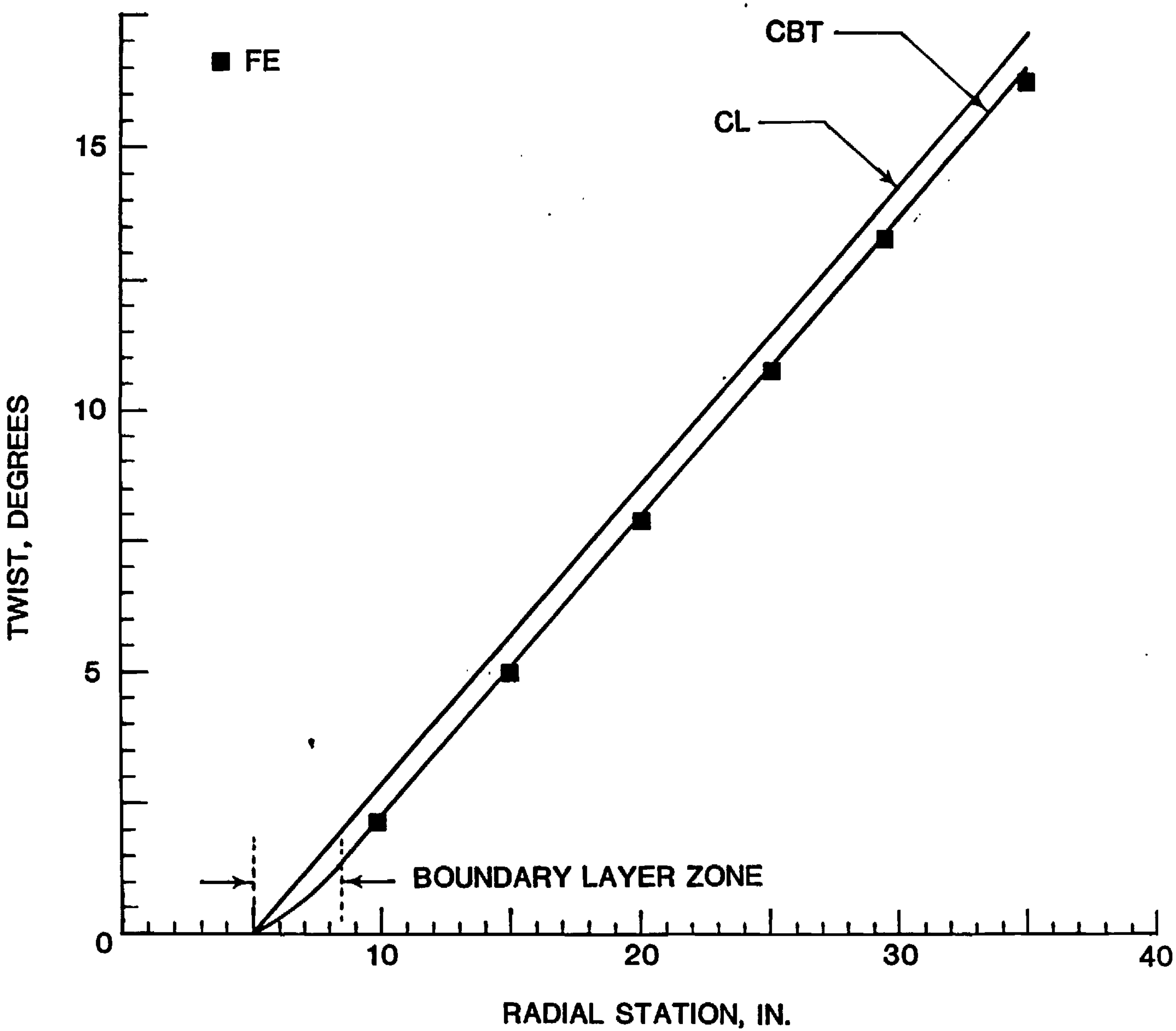


FIGURE 3

TWIST DUE TO APPLIED TORQUE

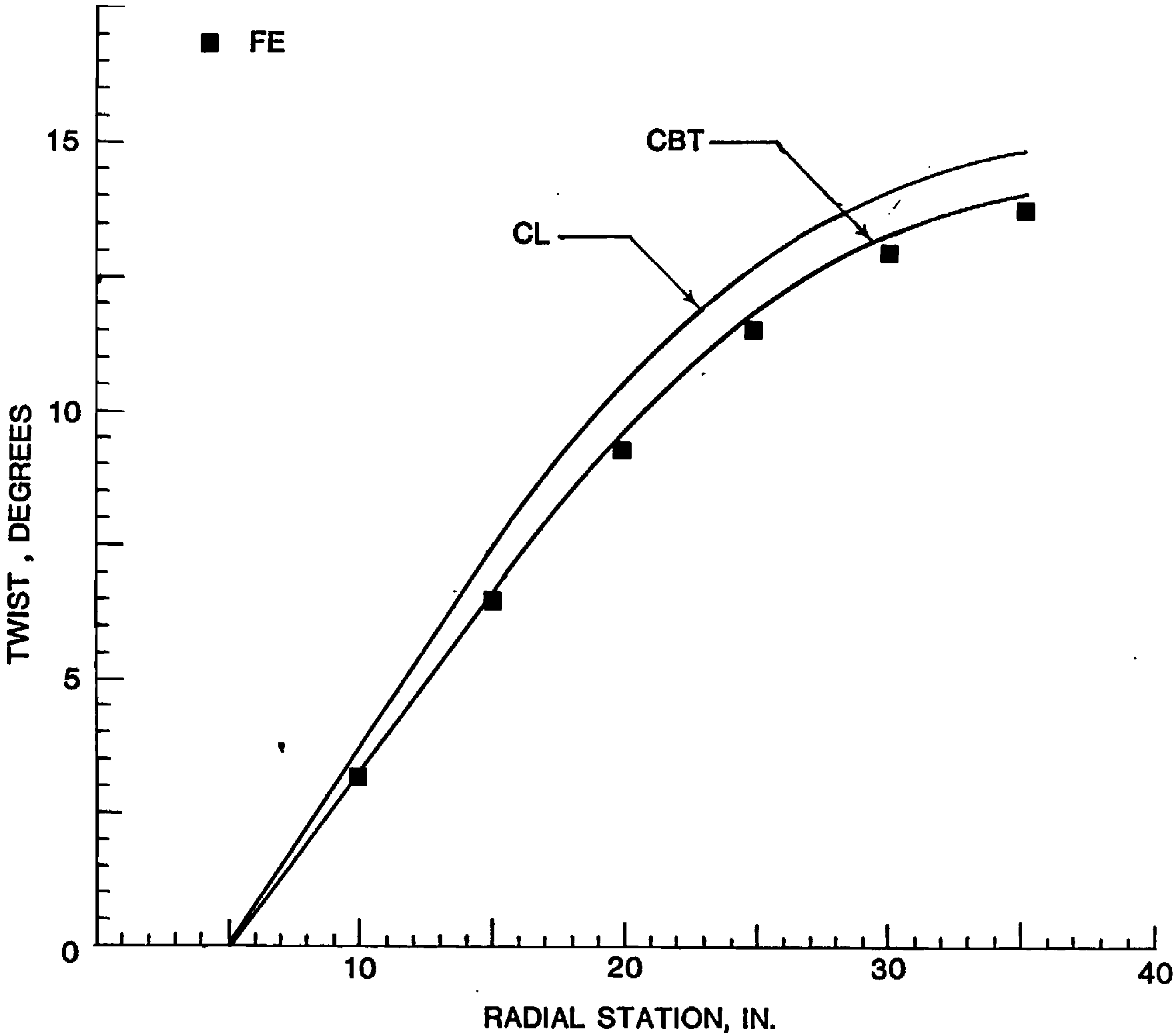


FIGURE 4

TWIST DUE TO CENTRIFUGAL FORCE

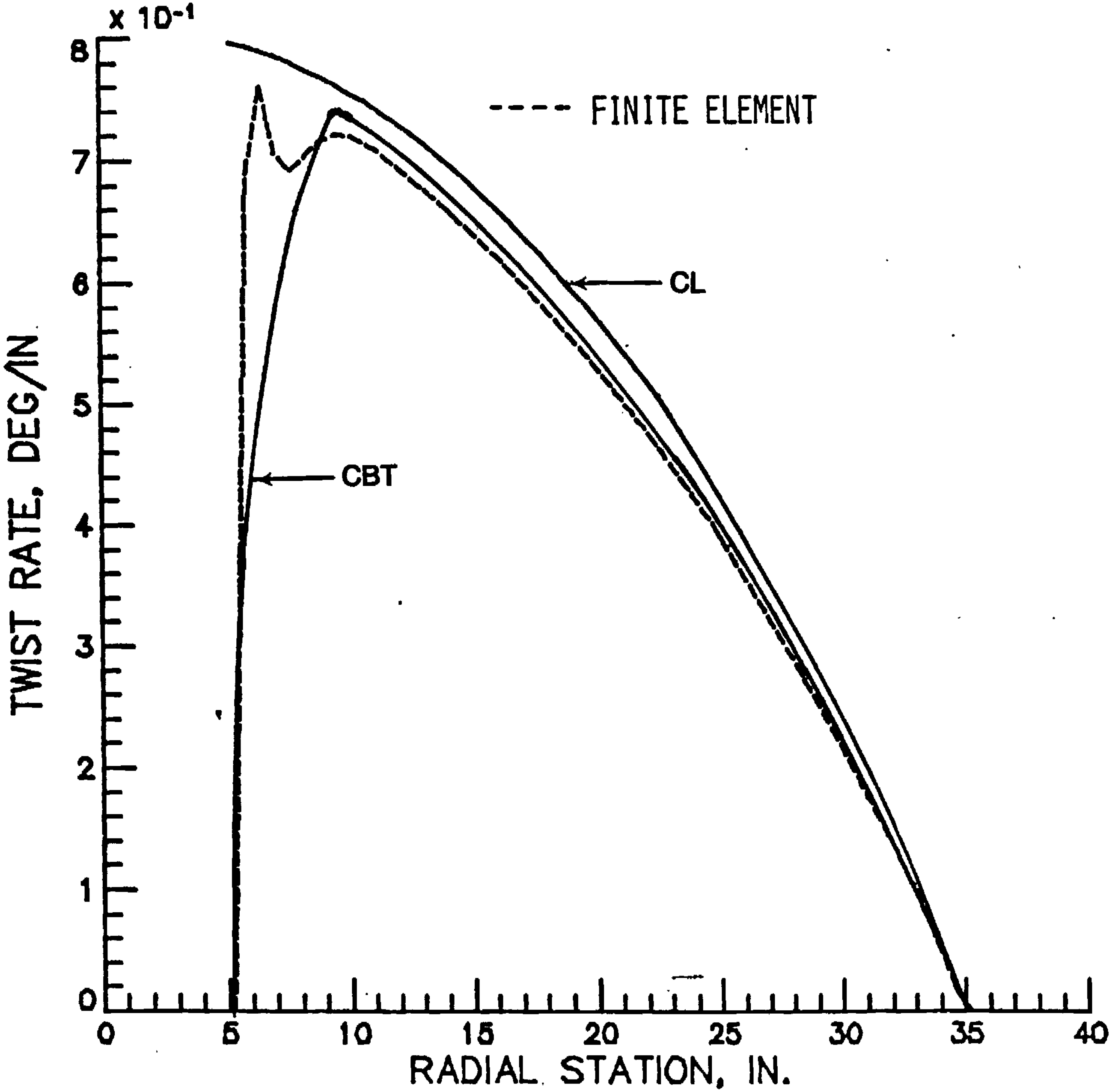


Figure 5. - Twist rate due to centrifugal force.

E-16-625 F

A CENTER OF EXCELLENCE

FOR

ROTARY WING AIRCRAFT TECHNOLOGY

FINAL REPORT

AUTHORS:
R. B. Gray
D. P. Schrage
J. I. Craig
S.V. Hanagud
S. S. Klein
N. M. Komerath
C. M. McKeithan
H. M. McMahon
D. A. Peters
G. A. Pierce
L. N. Sankar
L. W. Rehfield
J. C. Wu

25 February 1988

U. S. ARMY RESEARCH OFFICE

CONTRACT DAA29-82-K-0094

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF AEROSPACE ENGINEERING

A CENTER OF EXCELLENCE

FOR

ROTARY WING AIRCRAFT TECHNOLOGY

FINAL REPORT

AUTHORS:
R. B. Gray
D. P. Schrage
J. I. Craig
S.V. Hanagud
S. S. Klein
N. M. Komerath
C. M. McKeithan
H. M. McMahon
D. A. Peters
G. A. Pierce
L. N. Sankar
L. W. Rehfield
J. C. Wu

25 February 1988

U. S. ARMY RESEARCH OFFICE

CONTRACT DAA29-82-K-0094

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF AEROSPACE ENGINEERING

FOREWORD

The Army's tactical and operational level doctrine, called AirLand Battle, places a heavy reliance on force flexibility and agility to fight the deep, close, and rear area battles. Vertical Takeoff and Landing (VTOL) aircraft systems, operating from unprepared surfaces, provide the Army the capability to execute AirLand Battle Doctrine on the modern battlefield. Rotary wing aircraft have evolved as the only viable VTOL concept for U.S. Army applications due to their (1) inherent low disk loading and downwash velocities which allow operation from unprepared surfaces, (2) excellent hovering performance and fuel efficiency, and (3) excellent low speed controllability. Figure 1 illustrates the efficiency of the rotor versus other VTOL concepts.

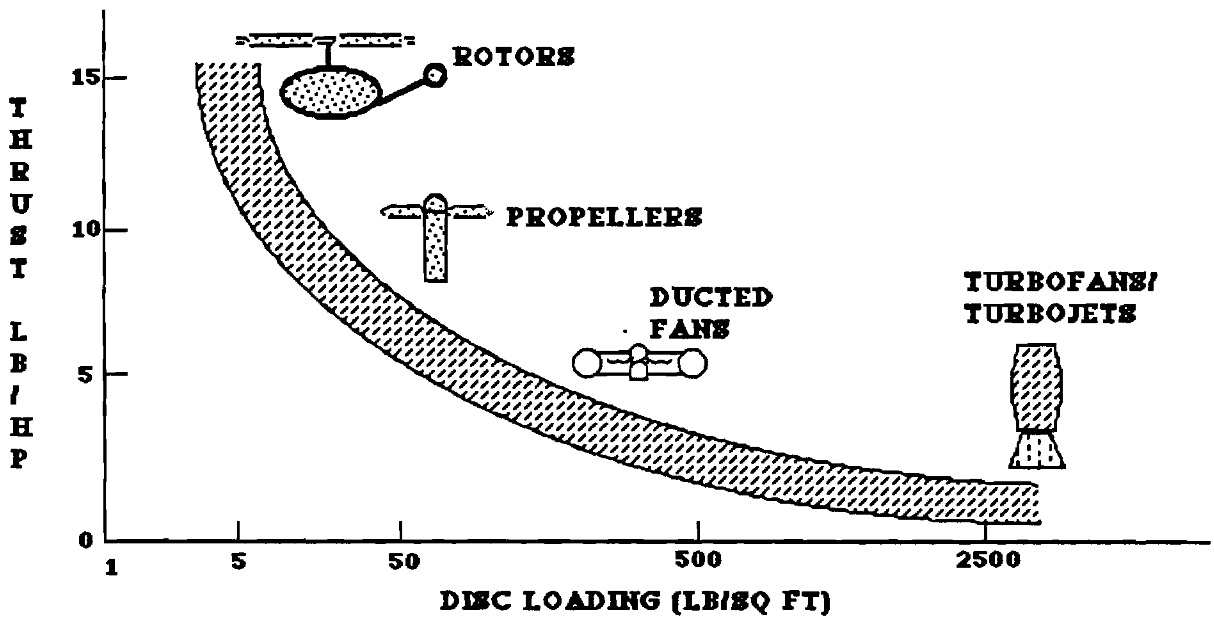


Figure 1. Hover Efficiency of VTOL Aircraft

Like most VTOL aircraft, however, rotary wing aircraft are complex and require an interdisciplinary approach to understanding their unique characteristics and how to best exploit them. The interdisciplinary interaction that takes place in real time in a typical flight condition is illustrated in Figure 2. The technical disciplines involved are aerodynamics, aeroelasticity, structure and materials, and flight mechanics and controls. This complex interaction is found on any rotary wing aircraft wing aircraft whether it be a conventional helicopter, tilt rotor aircraft, or any unique hybrid configuration.

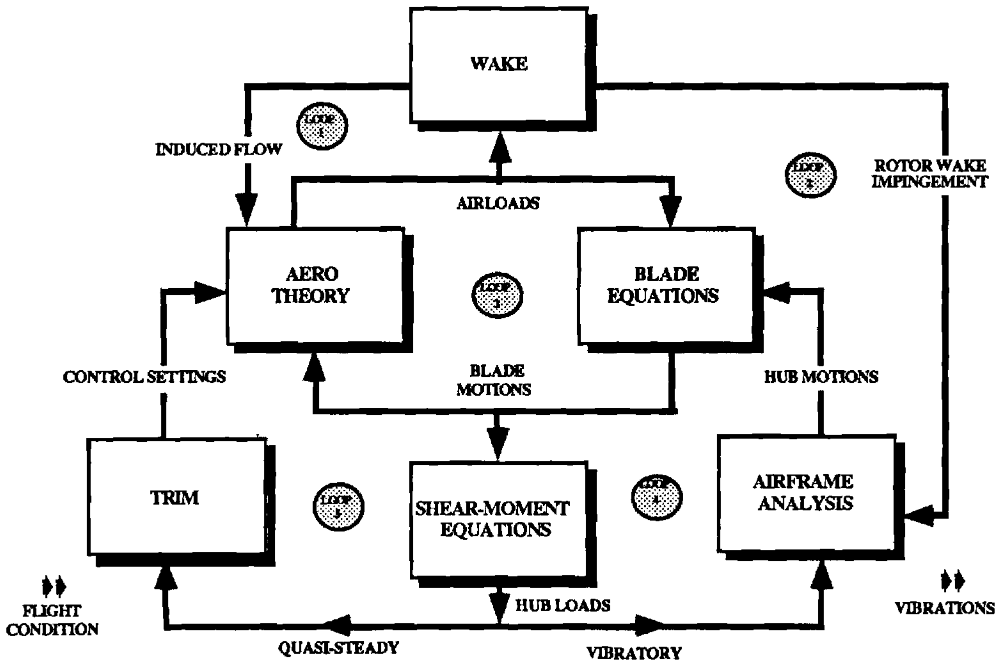


Figure 2. Rotorcraft Interdisciplinary Interaction

As illustrated in Figure 2, the interactions are a series of coupled feedback loops between one or more disciplines. For instance, loop 1 shows the feedback of the rotor wake into the aerodynamic theory. Loop 3 is an aeroelastic loop which illustrates the blade response to aerodynamic excitation. Table 1 is a summary of all the loops in Figure 2 and illustrates the necessary coupling between the principal and supporting disciplines in each loop.

TABLE 1.

NECESSARY COUPLING FOR ROTORCRAFT INTERDISCIPLINARY INTERACTION

INTERACTIVE LOOPS OF FIGURE 2

Discipline Area	Loops 1&2	Loop 3	Loop 4	Loop 5
Aerodynamics	P	S	S	S
Aeroelasticity	S	P	S	S
Structures & Materials	S	S	P	S
Flight Mechanics & Controls	S	S	S	P

P - Principle Discipline S - Supporting Discipline

For different flight conditions and different types of calculations, certain loops take on increased importance. For instance, the interactional aerodynamics loop 2 is most important during low speed transition for flying qualities and high speed flight for fatigue loads. Obviously, to be able to accurately calculate vibrations throughout the entire flight envelope requires all the interaction in Figure 2. Programs such as the Army's Second Generation Comprehensive Helicopter Analysis Program (2GCHAS) are trying to take a systems approach to the Figure 2 interaction problem. Georgia Tech's Center of Excellence in Rotary Wing Aircraft Technology (CERWAT) has made great strides during its first five years in developing a center that can address the complex interaction loops of Figure 2 and is now in a unique position to make major contributions in the future. This position has been achieved by accumulating the necessary critical mass of rotary wing expertise, the required leadership and management philosophy, and by developing the necessary academic curriculum and facilities to support such an effort.

The principal CERWAT faculty and staff with their primary academic and research areas of concentration are provided in Table 2. The management and organizational structure for CERWAT is provided in Figure 3.

TABLE 2.

Georgia Institute of Technology

CERWAT

FACULTY ACADEMIC & RESEARCH DISCIPLINE CONCENTRATIONS

	Aerodynamics	Aeroelasticity	Structures & Materials	Flight Mechanics & Controls
Professor				
	R. B. Gray	G.A. Pierce	L.W. Rehfield	D.P. Schrage
	J.C. Wu	D.A. Peters	S.V. Hanagud	A.J. Calise
	H.M. McMahon	D.H. Hodges	J.I. Craig	
		D.P. Schrage	D.H. Hodges	
Assoc. Professor				
	N.L. Sankar			
Asst. Professor				
	N.M. Komerath		E.I. Armanios	
Research Engineer				
	W. Tang	S.S. Klein	M. Meyyappa	P. Jonnalagadda
		A. Anand		

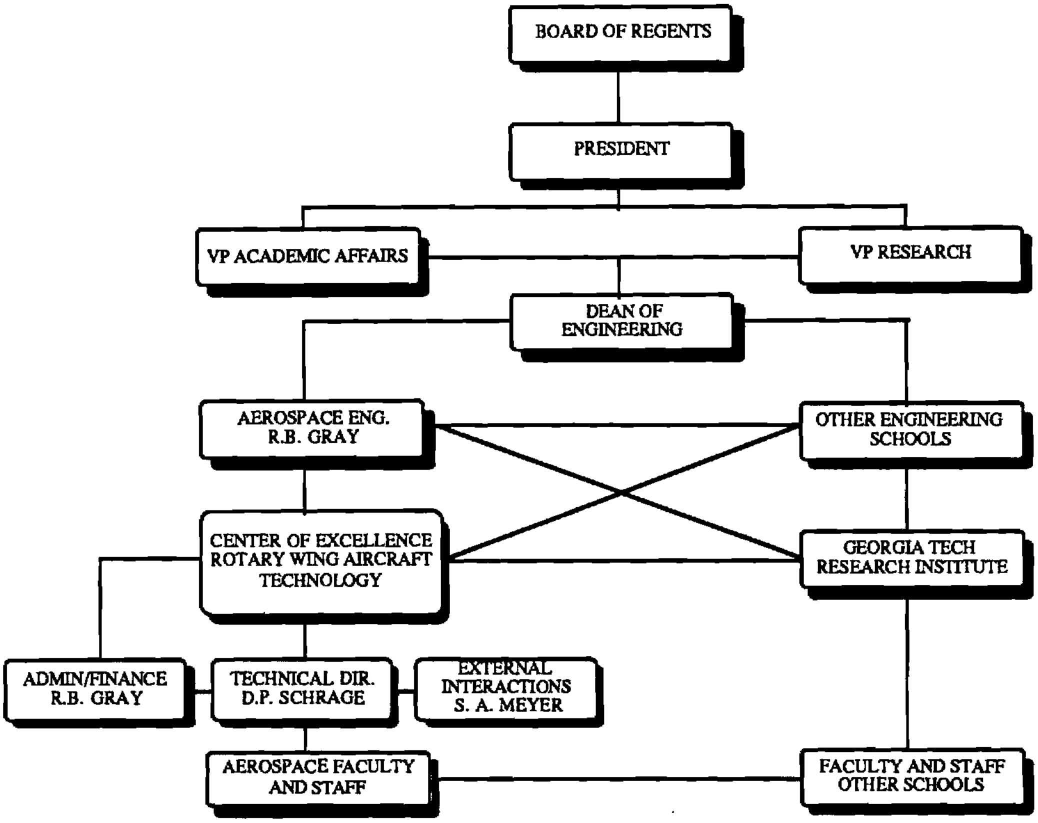


FIGURE 3. CERWAT Organizational Chart within Georgia Institute of Technology, a Unit of the University System of Georgia

RECORD OF PAST ROTARY WING ACCOMPLISHMENTS

Georgia Tech's School of Aerospace Engineering has an outstanding reputation in furthering rotary wing aircraft technology which dates back to the School's inception in 1930 under one of the six Guggenheim Grants to establish U.S. schools of aeronautics. Montgomery Knight, the School's first director, made major contributions to the understanding of ground effect benefits for rotary wing aircraft. Basic courses in rotary wing theory have been taught continuously since the 1940's by such renowned individuals as Walter Castles and Robin Gray. This emphasis on rotary wing aircraft was strengthened in the 1960's and 1970's as the Army sent many military officers and civilian employees to Georgia Tech to take advantage of one of the nation's few rotary wing aircraft programs. Many of these individuals have gone on to become the rotary wing leaders in government and industry.

Since becoming a U.S. Army Center of Excellence in Rotary Wing Aircraft Technology (CERWAT) in 1982, as a result of the Vertical Lift Technology Review sponsored by the Assistant Secretary of the Army for Research, Development and Acquisition in 1980, Georgia Tech has established itself as the leading rotary wing university in the world. This claim can be substantiated in a number of ways: the faculty accumulated; the research conducted; the curriculum developed; the symposia held; the design awards won; and the graduates produced. The faculty accumulated, as listed in Table 2, is unmatched in terms of rotary wing quality, quantity, and experience. It includes theoreticians, analysts, experimentalists, and leaders with U.S. Army and rotary wing operational experience. The breadth and depth of rotary wing research can best be appreciated by reviewing the publications listed in the Bibliography published later in this report. The Curriculum developed and expanded is provided in Table 4, and is the most comprehensive set of rotary wing courses ever assembled at one university.

TABLE 3.

GEORGIA TECH ROTORCRAFT ACADEMIC PROGRAM GROWTH 1982 - 1987

		Existing	New	Updated	Professor
4400	Introduction to Propellor and Rotor Theory	x			Gray
4600	Computational Aerodynamics		x		Sankar/Wu
6022	Advanced Compressible Flow III			x	Sankar
6400	Rotor Aerodynamics I	x			Gray
6401	Introduction to Helicopter Stability and Control II	x			Gray
6402	Aerodynamics of the Helicopter III		x		Gray
6802	Numerical Fluid Dynamics III		x		Wu
6810	Unsteady Aerodynamics		x		Wu
6030	Advanced Potential Flow I			x	Pierce
6031	Advanced Potential Flow II			x	Pierce
6200	Advanced Aeroelasticity I			x	Pierce
6201	Advanced Aeroelasticity II			x	Pierce
6202	Experimental Aeroelasticity			x	Pierce
8103	Rotorcraft Dynamics and Aeroelasticity I		x		Peters
8123	Rotorcraft Dynamics and Aeroelasticity II		x		Hodges
4115	Introduction to Fiber Reinforced Composites		x		Rehfield
4116	Manufacture of Composite Structures		x		Rehfield
6106	Finite Deformation of Aircraft Structures		x		Rehfield
6132	Vibration Measurement and Analysis		x		Craig
6133	System Identification		x		Hanagud
8104	Rotorcraft Design I		x		Schrage
8114	Rotorcraft Design II		x		Schrage
8113	Flight Mechanics and Controls		x		Calise
8133	Flight Dynamics and Controls		x		Calise

Since 1983, Georgia Tech has sponsored seven rotary wing related symposia as listed in Table 5.

TABLE 4.

Georgia Institute of Technology CERWAT Conferences, Symposia and Short Courses
APPLICATION OF A SYSTEMS APPROACH TO ADVANCED ROTORCRAFT DESIGN AND TECHNOLOGY ASSESSMENT, Atlanta, GA, Sept. 11-13, 1985
US ARO/CERWAT CONFERENCE ON DYNAMICS AND AEROELASTIC STABILITY MODELING OF ROTOR SYSTEMS, Atlanta, GA, Dec. 4-5, 1985
AMERICAN HELICOPTER SOCIETY NATIONAL ROTORCRAFT SPECIALIST'S MEETING ON CRASHWORTHY DESIGN OF ROTORCRAFT, Atlanta, GA, Apr. 7-9, 1986
A SYSTEMS APPROACH TO ADVANCED ROTORCRAFT DESIGN AND TECHNOLOGY ASSESSMENT, Atlanta, GA, Jun. 23-27, 1986
WORKSHOP ON APPLICATIONS OF THE DYNAMIC SYSTEMS COUPLER (DYSCO) MODELING PROGRAM, Atlanta, GA, Dec. 16-17, 1986
ROTORCRAFT ANALYSIS AND DESIGN, USA AVSCOM, St. Louis, MO, Mar. 23-27, 1987
FOCUS ON COMPOSITE MATERIALS, Atlanta, GA, Jun. 9-12, 1987

Georgia Tech's CERWAT student design teams have won seven of the nine awards given for the AHS/Boeing Vertol Student Design Competitions. Georgia Tech's students have won more Vertical Flight Foundation (VFF) fellowships over the last five years than any other university. Graduated CERWAT fellows are making major contributions in the rotorcraft industry and government laboratories.

This final report for the first five years of the CERWAT program provides a summary of the results of this Army Research Office sponsored research.

TABLE OF CONTENTS

LIST OF APPENDICES, ILLUSTRATIONS, AND TABLES

Appendices:

Illustrations:

Tables:

RESEARCH TASKS

A. Aerodynamics Tasks:

Task 1. Experimental Studies for Tip Vortex Core Modeling

Investigators: R. B. Gray and N. M. Komerath

Problem Studied:

The objectives of this task were to develop a capability for measuring the flow field near the tip and in the wake of a hovering helicopter model rotor using a laser velocimeter and to use the data to guide the development of a tip vortex core model for use in free wake analyses for blade loading predictions.

Summary of Results:

A two-component laser doppler velocimeter system was purchased and installed, and was used to generate an extensive and detailed database on the flow field of a single-bladed rotor in hover. Seeding and data acquisition and processing techniques were developed to enable these measurements, and the use of this instrument became routine in this facility.

The inflow and near wake regions of the rotor were documented in detail, and the data have since been used to validate two codes at Georgia Tech, as well as one at McDonnell-Douglas. Two AIAA Conference papers and one Journal of Aircraft publication resulted from these measurements.

The technique of laser sheet flow visualization was adopted and developed at this facility to enable qualitative observation and quantitative documentation of the dynamics of the tip vortex system. For the first time, this technique was applied to uniformly seeded flow fields, where the vortex core cross-sections became visible due to their lack of light-scattering seed particles. Up to three turns of the vortex could be photographed. Quantitative measures were obtained of the core size and unsteadiness of the vortex as a function of age. The work done on this task has since resulted in major advances in other tasks, notably task 5, and also served to guide precise LDV measurement of the vortex core. This work was initially performed as an undergraduate Special Problem, which was presented as a Student Paper at the AIAA Regional Student Conference.

To make velocity measurements in the core of the tip vortex, it was found to be essential to use seed particles which were small enough to stay and follow the flow in the highly accelerated inner core. Suitable particles were found (incense smoke), but they could not be observed in back-scatter by the LDV. This problem was solved by developing, for the first time, a remote-aligned off-axis scatter receiving system. This system enabled detailed measurement of the velocity profiles inside the core of the tip vortex. For the first time, the component of velocity along the axis of these rotary-wing tip vortices was measured as well. Complex secondary structures were found inside the core, showing that the roll-up process of the vortex sheet into the tip vortex must be included in constructing vortex core models. This work resulted in a Ph.D. Thesis, an AIAA Conference paper, and a Journal of Aircraft publication. The data base awaits development of prediction techniques capable of modeling this flow field.

The problem of particle lag in vortex flows, and the attendant difficulties in making accurate LDV measurements, led to work on modeling and correcting for particle lag. To date, a numerical procedure has been developed for correcting measurements made in accelerating flow around a three-dimensional source. This work is being extended to vortices in uniform flows. At the same time, work has also been performed on a method to simultaneously measure velocity and particle size in such facilities. These efforts have resulted, to date, in one undergraduate Special Problem and three MS Special Problems.

Efforts to validate Navier-Stokes computations of the blade tip flow field using the data acquired in this task have resulted in two Conference papers.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 2. Modification of Blade Tip Loading to Improve Hovering Figure of Merit

Investigators: R. B. Gray and T. Thompson

Problem Studied:

Measured pressure distributions on the tip of a hovering model rotor blade show a low pressure region which is associated with the roll-up and rearward sweep of the tip vortex over the trailing 50% for the blade upper surface. This low pressure region near the trailing edge contributes significantly to the section pressure drag and hence to the rotor power required. The objective of this task is to explore the possibilities of improving performance by modifying the tip pressure distribution.

Summary of Results:

This task was completed and a final report was written in 1986 (Ref. 2.1.3).

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 3. Prediction of Flow Around Blade Tips

Investigators: L.N. Sankar, R. B. Gray, W. Tang, R. Srivastava, O. Kwon, B. E. Wake

Problem Studied:

The objective of this research task is to develop a procedure to accurately predict the flow field and hence the airloads in the vicinity of the tip of a rotor blade. This requires an accurate modeling of the tip vortex formation and roll up processes, and capture of the strength and location of embedded shock waves.

Summary of Results:

Two approaches were developed for study of this problem. First, a panel code capable of handling isolated rotor blades in hover or in forward flight was developed by O. Kwon, a graduate student. This code uses panels of constant source and doublet strengths to account for the thickness and lift effects respectively. The shed vortices from the tip were modeled using a prescribed wake model developed by Gray for hover applications. In forward flight applications, a free wake model developed by Scully was used. The vortex geometry in the vicinity of the blade tip was parametrically modified to determine the effects of the various tip vortex parameters on the predicted surface pressure distribution.

A version of this solver has been coupled to a curved beam nonlinear structural model developed by Hodges, and may be used to evaluate the static stability characteristics of modern rotor blades of arbitrary planform. As part of his Ph.D. thesis, O. Kwon is working on extending the above analysis to predict dynamic instability of rotor blades.

A hybrid time marching scheme for solving three-dimensional compressible Navier-Stokes equations developed under Aerodynamics Task 4 was adapted in the present work to study three-dimensional, unsteady, compressible flow past rotor blades. The resulting computer code is capable of handling rotor blades of arbitrary planform and can predict the flow around the entire rotor disk, including massively separated flows that may occur over the retreating side. If viscous effects are not important, this solver may be used as an Euler code to reduce the computer time.

In a cooperative effort with the scientists at the U.S. Army Research Laboratory, this solver was coupled with the free wake model embedded in the CAMRAD code, and was evaluated through the following benchmark calculations, performed in the Euler mode:

a) NACA 0012 rotor of rectangular planform, tip Mach number 0.7, advance ratio 0.3, zero degree collective pitch.

b) NACA 0012 rotor of rectangular planform, tip Mach Number 0.8, advance ratio 0.2, zero degree collective pitch.

c) A 1/7th scale model of the Cobra OLS rotor, tip Mach number 0.663, advance ratio 0.28. In this case, the collective pitch was iteratively adjusted using a procedure originally developed by Tung and Caradonna[1] to match the computed thrust coefficient with the experiment.

d) A three-bladed rotor tested in France.

In all the cases studied, very reasonable agreement with experiments was obtained.[2]

As part of his Ph.D. thesis work, B. E. Wake repeated calculations a) and b) mentioned above using the Navier-Stokes version of the code, and demonstrated that the viscous effects weaken the shock, and tend to place it forward of the Euler results. Viscous flow calculations were also carried out for a NACA 0012 rotor of rectangular planform in hover.[3]

A version of this solver capable of handling 3-D blade vortex interaction was developed and correlated with experiments. [2]

Detailed comparisons of the velocity field predicted by the 3-D Navier-Stokes solver for a model rotor blade in hover, tested under Aerodynamics Task 1, demonstrate that this solver provides a good quantitative modeling of the velocity field around the rotor blade. The velocity vector plots around the tip of the rotor blade which show the formation of the tip vortex are in good agreement with experiments.[4]

In a joint study between Bell Helicopter Textron, Cray Research and the present researchers, this 3-D Navier-Stokes code is being used to evaluate the massively separated flow over a rotor blade in a high-G maneuver.[5]

Technology Transfer:

Latest versions of this computer code have been made available to United Technologies Research Center (A. Egolf, B.E. Wake), McDonnell-Douglas Helicopter Co. (A. Hassan), Bell Helicopter Textron (J. Narramore), and the U.S. Army Aeroflightdynamics Directorate (C. Tung).

Lockheed Georgia Co. has obtained a version of this solver, and has adapted it for fixed wing aeroelastic applications.

Under the support of the NASA Lewis Research Center, a version of the 3-D Navier-Stokes solver capable of analyzing fixed wing performance under leading edge icing is being developed.

References:

1. Tung, C; Caradonna, F.X.; Boxwell, D.A.; and Johnson, W.R., "The Prediction of Transonic Flow on Advancing Rotors", *Proceedings of the 40th Annual National Forum of the American Helicopter Society*, May 1984.

2. Sankar, L.N. and Tung, C., "Euler Calculations for Rotor Configurations in Unsteady Forward Flight", *Proceedings of the 42nd Annual Forum of the American Helicopter Society*, June 1986.

3. Wake, B.E., "Solution of the Navier-Stokes Equations Applied to Rotors", *Ph.D. Dissertation*, April 1987.

4. Sankar, L.N. and Komerath, N.:M., "Measurement and Computation of the Flow Around the Tip of a Lifting Rotor Blade in Hover", *AIAA Paper 88-0047*, 1988.

5. Narramore, J., Sankar, L.N. and Vermeland, R., "An Evaluation of a Navier-Stokes Code for Calculation of Retreating Blade Stall on a Helicopter Rotor", To be presented at the 44th Annual Forum of the American Helicopter Society, 1988.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 4. Studies of Unsteady Rotor Aerodynamics

Investigators: J.C. Wu, L.N. Sankar, M. Patterson

Problem Studied:

The primary objective of this work was to develop efficient computational tools for ;the prediction of the aerodynamic characteristics of airfoil. These tools should be capable of generating the static load characteristics of advanced airfoil configurations (Lift vs. Angle of Attack, Drag Polar, Drag vs. Mach Number), and should be capable of predicting the dynamic stall characteristics of airfoils. A second objective of this research effort was the development of efficient solution algorithms for the prediction of 3-D unsteady viscous flow over rotor blades.

Summary of Results:

Two computer codes were developed as part of this work. The first computer code solves the incompressible viscous flow over airfoils of arbitrary shape using an efficient zonal procedure. The flow field over the airfoil undergoing dynamic stall is usually attached over the lower surface, and separated over the upper surface. The zonal procedure solves the unsteady boundary layer equations written in the vorticity-stream function form over the lower surface. Only in the massively separated region over the upper surface is computation performed using the full Navier-Stokes equations, written in the vorticity-stream function form. The attached and separated flow regions are coupled to each other through the Poisson's equation for the stream function, and was solved in this work using an integral representation.

Efficient solution procedures were developed for the computation of the stream function at every time step as a function of the vorticity field., Procedures were also developed for the computation of new vorticity generated at the solid surface at every time step. As a result, an extremely efficient computer code has resulted which can predict the static load characteristics of any airfoil for the entire range of interest (from 0 degree angle of attack to post-stall angles of attack) within 10 minutes of CRAY XMP computer time. The same solver can be used to compute dynamic stall hysteresis loops for a given airfoil within one minute of CRAY XMP time per flight condition.

The second computer code developed solves the 2-D compressible Navier-Stokes equations in a strong conservation form using an alternating direction implicit (ADI) time-marching scheme. This solver may be used when compressibility effects are important. The governing equations are solved in a coordinate system that is free to rotate with the airfoil. The airfoil may also undergo sinusoidal flapping and/or lunging motion. This solver requires about 40 minutes of computer time on a CRAY XMP to generate the static stall characteristics, and about 2 hours of CRAY XMP time to generate a dynamic stall loop.

Both the flow solvers have been validated by correlating the computed results with the experimental data obtained by Carr, McAlister, and McCroskey. Excellent agreement with experiment has been obtained. The code validation studies have been documented in open literature (see Bibliography).

Special versions of the incompressible and compressible Navier-Stokes solvers were developed which may be used to study the 2-D Blade-Vortex-Interaction (BVI) problem. These solvers can handle weak interactions as well as strong interactions where the vortex collides with the airfoil and causes large disturbances within the boundary layer.

A version of the incompressible Navier-Stokes solver that can handle circulation control applications was also developed. Because conventional circulation control techniques that rely on the tangential blowing of air jets over the airfoil upper surface are well understood, effort was focused on the use of solid surface motion to postpone or avoid stall. In this approach, a portion of the airfoil surface is free to move in the direction of the flow, say through the use of a rotating cylinder positioned at the nose of the airfoil. These studies indicate that very small surface velocities are often adequate to postpone stall or completely avoid stall on the retreading side of the rotor disk.

Some work was also done towards development of efficient algorithms for calculation of 3-D unsteady viscous flow. Pilot versions of 3-D incompressible flow solvers that use pressure-velocity formulation, and velocity-vorticity formulation were developed. A hybrid (explicit-implicit) time marching scheme for the 3-D compressible Navier-Stokes equations, as well as 3-D grid generation schemes that can handle rotor blade geometries of arbitrary planform were developed as part of this research task. The 3-D compressible flow solver was made available to Aerodynamics Task 3 to tip vortex studies.

Technology Transfer:

The computer codes developed as a part of this task have been distributed to U.S. helicopter companies, government laboratories, and universities. The following agencies have received and routinely use the computer codes:

a. NASA - Ames Research Center (Larry Carr and Prof. Bodapadi: Dynamic Stall Studies)
b. NASA - Lewis Research Center (K.R.V. Kaza, Reddy and Dennis Huff: Propfan Studies, Stall Flutter, Airfoil Icing, k-ε turbulence models)
Blade Vortex Interaction Studies)
d. McDonnell-Douglas Helicopter Company (A. Hassan: Dynamic Stall Studies)
e. Bell Helicopter Textron (Steve Fodelsky: Dynamic Stall Studies, Flapping and Lunging Motion Applications)
f. Duke University (E. Dowell: Transonic Flutter Applications)

During the period 1985-1987, small research grants from the McDonnell-Douglas Helicopter Company and NASA Lewis Research Center also resulted as a result of the progress made in the present research task, and led to modifications to the computer codes for specialized applications.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 5. Studies of Rotor-Airframe Aerodynamic Interactions

Investigators: H.M. McMahon and N.M. Komerath

Problem Studied:

This task aimed to develop a physical understanding of aerodynamic interaction phenomena between the rotor and airframe of rotorcraft. The database developed was to be used in validating and developing prediction methods for rotor-airframe interactions.

Summary of Results:

An integrated experimental/numerical approach has been used. To keep the problem tractable, the simplest generic rotor/airframe configurations have been employed, but a variety of techniques have been used to enable clear definition of the flowfield and its effects.

The Low-Speed Wind Tunnel at Georgia Tech was modified into a Forward Flight Facility with a powered rotor installation and a modern control room and digital data acquisition system. Software for pressure surveys, probe traverses, LDV data acquisition, time-series analysis, rotor dynamic balancing, and high-speed time history acquisition have been developed and used.

A detailed data base has been accumulated on mean and time-resolved surface pressure distributions on the airframe surface for a range of variation of advance ratio, and vertical and horizontal rotor-airframe separation, with two different rotors. The data have been published as a Data Report, which has been transmitted both in document and electronic forms to industry, university, and NASA researchers at their request. Two Conference papers and an AIAA Journal publication (under review) have resulted from this effort.

The mean and time-resolved velocity field near the airframe and the rotor, and airframe effects on the rotor flow field, have been documented in an extensive and unique set of measurements made using the laser velocimeter. Besides demonstrating routine LDV operations in this wind tunnel, these tests have provided precise quantitative information on the complex velocity field, including vortex interaction effects on the rotor and airframe, secondary vortex generation at the rotor disc edges, the effects of the rotor hub, and the inflow to the rotor disc. These have been published in two Conference papers, and one Journal of Aircraft paper (under review).

Major strides have been taken in applying laser sheet flow visualization to the rotor-airframe flow field. The trajectories and dynamics of the vortex system of the rotor have been documented in detail. Secondary vortex generation phenomena and vortex interactions with the airframe have been captured. Distortions to the trajectories caused by the airframe have been measured. One Conference paper and two Journal of Aircraft publications (one accepted, the other under review) have resulted from this effort.

Vortex-surface interactions have been closely studied by the synchronized application of pressure sensing, LDV measurements, and flow visualization. The results have been documented in a publication submitted for peer review.

Existing prediction codes including the Freeman-Hess code and the VSROTOR code were examined against the experimental data. It was found that the inclusion of a time-resolved rotor wake was essential to useful prediction, and hence work on a new code was started. Modified forms of Scully's Free Wake code and the AMI VSAERO body panel code have been linked. Success has been achieved in predicting mean pressure distributions over the airframe surface, and progress has been made towards a full prediction of the periodic pressure and velocity variations.

The experiments have produced a set of test cases where interaction effects between the rotor and airframe are very significant and measurable. However, the multi-faceted measurements have shown that most of the interaction effects are consistent with simple potential-flow models, and that the dominant features of the flow field are accessible to prediction by relatively simple techniques. More complex effects such as massive flow separation around the airframe and rotor aeroelastic phenomena are subjects for future test cases.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

B. Structures Tasks

Task 1. Structural Dynamic System Identification

Investigators: S.V. Hanagud, J.I. Craig, M. Meyappa, S. Sarkar, Y. Yillicki

Problem Studied:

The objective of this task is to develop techniques to effectively identify structural dynamic models that realistically and accurately describe physical structural systems. The research has concentrated on both measurement and analysis methods and has considered the effects of simple nonlinearities, nonproportional damping and large concentrated masses. The most recent work has been directed at the problem of rotor blade system identification with particular interest in the damping characteristics and the uniqueness of the identification. The current work is concerned primarily with fundamental techniques for identification of distributed parameter models that uniquely describe physical systems.

Summary of Results:

Structural dynamic models have been developed including damping by using identification techniques and experimental results. Techniques have also been developed for the identification of structural dynamic models with nonproportional damping from experimental measurements. Aeromechanical equations in a concise form have been developed by using Kane's and Gibb's method. These will be used in programs like the Army's 2GCHAS. Multiple scale identification procedures have been developed to formulate nonlinear systems.

Artificial Intelligence based techniques of model identification were developed by using A^* search and object oriented programming techniques. Another accomplishment was the use of scale models in structural dynamic testing as well as development of methods of using identification and elastic fuselage models in vibration control. Methods of vibration control were developed by using lightweight sensors and actuators mounted on the structure (piezoceramic sensor and actuators) with possible application to Individual Blade Control (IBC).

Other results of this research include the prediction of random-like responses (in blades and fuselage) which are in reality not random vibration, but a new concept known as chaotic vibration in deterministic systems. Also developed were computer-aided engineering methods for structural dynamics systems.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 2. Crashworthy Characteristics of Composite Rotorcraft Structures

Investigators: S.V. Hanagud, J.I. Craig, R. Chander, P. Sriram, C.C. Won, and W. Zhou

Problem Studied:

The objective of this task was to conduct basic research to develop improved techniques and procedures for designing crashworthy composite structures for rotorcraft. This includes the development of analysis methods, testing techniques, and crashworthy design optimization under constraints of weight, cost, and performance.

Summary of Results:

Portable noncontact measurement techniques were developed for use in the laboratory and in field crash tests. Analysis, design and testing was conducted for curved web structures for energy absorption in crashworthy designs. A computerized Crash Energy Absorption Laboratory test facility was developed.

Also developed in this research were methods of optimization of structures. Static and dynamic test correlation of energy absorbing structures was performed. Accurate analytical models for the analysis of crash impact on energy absorbing and airframe structures were developed. Additionally, analysis was performed on flight data recorders for obtaining crash and crash test information.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 3. Concepts for Stability Critical Airframe Structures

Investigator: L.W. Rehfield

Problem Studied:

This task is concerned with crippling and postcrippling behavior of thin walled graphite/epoxy composite airframe members in axial compression. The main objectives are to 1) generate an experimental database on the crippling and postcrippling behavior, 2) develop simple analytical methods to predict these behaviors, and 3) provide better insight into the failure processes for this type of structure.

A second thrust concerns the structural modeling and analysis of composite rotor blades. The objective is to create an analysis methodology suitable for design which predicts response reliably and contains the capability of representing general composite construction. The opportunities presented by elastic tailoring utilizing the orientation effects that can be created with composite materials can be exploited easily with this analysis methodology.

Summary of Results:

Research findings pertaining to the concept of postbuckled structure is reported in publications listed in the bibliography. Emphasis has been given to analysis and correlation with previous experiments. A crippling law for no-edge-free composite plate elements has been created with a completely theoretical basis. The experimental data agree fairly well with the theory. It is based upon a maximum strain failure criterion.

A simplified analysis of composite plate elements has been created and is currently being evaluated for one-edge-free configurations. A new variational formulation has been created to characterize the situation being modeled. Simple, approximate solutions are currently being sought based upon the variational principle developed.

A very simple crippling law for one-edge-free elements has been established based upon a maximum strain failure criterion. It is presently being evaluated.

Rotor blade modeling results have been reported in the publications listed in the bibliography. In the course of this work, close working relationships were maintained with M.W. Nixon, R. Lake, G.L. Farley, and W. Mantay of the AVSCOM Aerostructures Directorate. Also, persons in the Aeroflightdynamics Directorate have been briefed on a regular basis.

The development of a theory valid for large deflections and moderate rotations has been completed. The single cell theory has also been improved. The improvements relate to twisting kinematics. These results are also reported in the publications in the bibliography.

A study has been completed which thoroughly develops the basis for extension-twist coupling in blades, the primary form of coupling useful for tilt rotor applications. Among the more important findings is the discovery that a single coupling parameter controls the structural design. General behavioral laws in terms of this parameter have been established.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

C. Aeroelasticity Tasks

Task 1. Helicopter Vibration Suppression Techniques

Investigators: G.A. Pierce, V. Anand, V.M Kaladi, Y.K. Kim, & D. J. Taylor

Problem Studied:

The overall purpose of this program is to develop and validate comprehensive vibratory analyses for the evaluation of vibration suppression techniques. The load analyses are to be applicable to nonuniform multibladed systems with various hub constraints. Special emphasis is to be placed on blade structural dynamics and unsteady blade aerodynamics.

To facilitate validation of the analyses, an aeroelastic rotor test chamber (AeroTech) has been developed. The primary purpose of AeroTech is to experimentally simulate and record various aeroelastic phenomena associated with contemporary helicopter systems. The information compiled with this facility will form a valuable data base with which to correlate the predictions obtained from newly developed analytical techniques.

This facility has a computer-based acquisition system which can simultaneously receive, condition, record and analyze up to forty-eight channels of response parameters. The on-line analysis of these data can be preprogrammed in FORTRAN-77 or can be processed by a time-series analyzer. The facility also has a three-channel hydraulic excitation system which permits on-line computer control of a swashplate mechanism for the dynamic excitation and control of the model rotor in blade pitch. Both static and dynamic calibrations of this actuator system have been installed in the computer, which has been programmed for stability and harmonic response testing.

Summary of Results:

Two comprehensive methods of analysis have been developed for the determination of elastic rotor blade response in forward flight. Both of these analyses are sufficiently general to handle nonuniform blades with various parametric offsets. Results obtained from these methods have been correlated with each other and published data from other analytical studies.

The first method of analysis is based on a new formulation of the blade equations for flap-lag-torsion deformations. A unique aspect of this formulation is in the treatment of the pitch control inputs. A transformation for the collective and cyclic control is performed prior to the transformation from undeformed to deformed coordinates. The spatial solution is obtained by a Galerkin technique with nonrotating modes, while the time dependency is computed by numerical integration.

The second method is an extension of the well-known structural dynamic development of Hodges and Dowell to include time-dependent pitch control inputs. This flap-lag-torsion representation has been programmed for solution using a harmonic balance technique by combining the previously used Galerkin approach with integer harmonic components for the generalized coordinates. This method provides two outstanding benefits. First, it is computationally very efficient; and secondly, it is ideally suited for the incorporation of unsteady aerodynamic formulations which are based on simple harmonic motion.

Dynamic testing has been performed on the ACR (Aeroelastically Conformable Rotor) model. This system is an articulated nine-foot diameter four-bladed rotor on loan from NASA Langley. Four types of response tests were conducted with this model. The first was a series of steady pitch control runs at various speeds and combinations of collective, longitudinal and lateral pitch settings. Secondly, a series of runs were made with a four-per-rev collective pitch about various mean collective settings and speeds. The third type of testing examined the transient behavior of the rotor system as the four-per-rev collective excitation was abruptly removed again at various mean settings and speeds. The fourth and final type of testing consisted of imposing various rapid ramp changes to the collective pitch at different speeds.

The HARP (Hughes Advanced Rotor Program) model was obtained on loan from McDonnell Douglas Helicopter Company (MDHC). This model is a bearingless eight-feet diameter four bladed rotor. Mechanical adapters have been designed and constructed so that the model can be tested in AeroTech. These tests were scheduled to begin earlier this year, but the model had to be returned to MDHC. The instrumentation on the blades is being replaced in preparation for a Whirl Test at the Ames facility and subsequent wind tunnel tests at the DNW facility in the Netherlands. It is anticipated that the model will be returned to AeroTech for additional dynamic testing during 1988. Plans are being made to include CERWAT personnel in the NASA/Army/MDHC test program and to make available much of the data obtained in these tests.

Technology Transfer:

Testing in the AeroTech facility has involved rotor systems from NASA Langley and MDHC. There is an on-going dialogue with these agencies and as further testing is accomplished, there will be a sharing of data between Georgia Tech and them.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

Task 2. Rotorcraft Aeroelastic Active Control Investigations

Investigators: D.P. Schrage and D.A. Peters

Problem Studied:

The objective of this task, which began during CERWAT's fifth year, was to study, evaluate and compare various controller configurations that have been shown either theoretically or experimentally to have the potential for providing favorable aeroelastic response and to improve unsteady aerodynamics representation with dynamics inflow. The research consisted of both an analysis and an experimental program.

Summary of Results:

The analysis program consisted of modelling various higher harmonic control (HHC) controller configurations and including them in a Dynamic Systems Coupler (DYSCO) program to investigate rotorcraft aeroelastic response. For the first time, an analytical free-flight simulation of HHC was reported utilizing and comparing five different HHC controllers. These five different controllers were incorporated into a dynamic response simulation of the OH-6A helicopter using the DYSCO flexible modeling system. The results were reported in K.P. Nygren's doctoral dissertation (Ref. 4.1.4), as well as his AHS Southeast Region Lichten Award-winning paper. These five HHC controllers were also applied to a DYSCO aeroelastic representation of the CERWAT AeroTech facility with Aeroelastic Conformable Rotor (ACR) blades and similar results were achieved.

Significant progress was also made in developing the dynamic inflow theory for use in aeroelastic response investigations. A strong correlation between dynamic-inflow theory and the lift-deficiency function of Loewy was found, which will allow simulation of an n-bladed rotor with dynamic-inflow by allowing n-pressure spikes to rotate around an actuator disk. These results have been reported in Reference 4.2.13.

On December 9-10, 1986, a DYSCO Workshop was sponsored by CERWAT and was held at Georgia Tech. Representatives from several AVSCOM laboratories, as well as the USAF Flight Dynamics Laboratory and Kaman Aerospace Corporation were in attendance. Presentations were made illustrating how the various controllers were incorporated into DYSCO. In addition, a discussion on dynamic-inflow and an approach on how it could be included in DYSCO was presented.

During the six-month extension to the fifth-year effort, the various controllers developed in the frequency domain for the fixed system HHC applications were extended to the time domain for Individual Blade Control (IBC) applications. The time-domain regulator used a frequency-shaped cost functional to minimize narrow band vibration levels. The dynamic model parameters are being identified with a least-squares/fourier series method with full state feedback. Plans are to extend the method to output feedback which will allow more practical application. The result of extending the various controllers to both the frequency and time domains will allow investigation of active control for a variety of aeroelastic response phenomena during follow-on efforts. The approach and results to date were reported in the Reference 4.1.14 paper and presentation and the Reference 4.2.15 presentation.

Also, during the six-month extension, we continued application of dynamic inflow. As a spin-off of this work, we received a grant from NASA Ames Research Center to develop an unsteady aerodynamic theory (based on dynamic inflow) for aeroelastic analysis. Under CERWAT, on the other hand, we continued quasi-steady application studies. These included application to measured static inflow of a rotor in forward flight as well as comparisons with Fridovitch's original collective-step response studies. Our results were as good as the free-wake results of Quackenbush. Lastly, we were able to show how dynamic inflow could be applied in a finite-element setting; and we began work on comparing dynamic-inflow results with those of a panel code also developed at Georgia Tech.

List of Publications and Technical Reports:

See Bibliography

Participating Scientific Personnel:

See Appendix 1

BIBLIOGRAPHY

1. CERWAT PUBLICATIONS

1.1 Notes of Short Course on Application of a Systems Approach to Advanced Rotorcraft Design and Technology Assessment, Atlanta, GA, September 1985

1.2 Proceedings of USARO/CERWAT Conference on Dynamics and Aeroelastic Stability Modeling of Rotor Systems, Atlanta, GA, December 1985

1.3 Proceedings of American Helicopter Society National Rotorcraft Specialist's Meeting on Crashworthy Design of Rotorcraft, Atlanta, GA, April 1986

1.4 Notes of Short Course on A Systems Approach to Advanced Rotorcraft Design and Technology Assessment, Atlanta, GA, June 1986

1.5 Proceedings of the Workshop on Applications of the Dynamic Systems Coupler (DYSCO), Atlanta, GA, December 1986.

1.6 Notes of Short Course on Rotorcraft Analysis and Design to USA AVSCOM, St. Louis, MO, March 1987.

1.7 Proceedings of Focus on Composite Materials, Atlanta, GA, June 1987.

2. AERODYNAMICS

2.1 Peer Reviewed Publications:

2.1.1 Wey, T.C. "A Numerical Analysis for Blade Tip Loadings on a Thick Bladed Rotor," Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, November 1983.

2.1.2 Wu, J.C., "Boundary Element Methods in Inhomogeneous Elliptic Differential Equations," Boundary Elements VII, Vol. 2, pp. 9-95, Springer-Verlag, June 1985.

2.1.3 Wey, T.C. and Gray, R.B., "A Numerical Investigation of Blade Tip Loadings on Thick-Bladed Helicopter Rotors," Journal of Computers and Mathematics with Applications, Vol. 12A. No. 1, pp. 53-83, 1986.

2.1.4 Sankar, N.L., Wake, B.E., Lekoudis, S.G., "Solution of the Unsteady Euler Equations for Fixed and Rotor Wing Configurations". AIAA Journal of Aircraft, Vol. 23, April 1986.

2.1.5 Gaonkar, H. and Peters, A., "Effectiveness of Current Dynamic--Inflow Models in the Correlation of Experimental Rotor Response Data in Hover and in Forward Flight," Journal of the American Helicopter Society, Vol. 31, No. 2, April 1986.

2.1 Peer Reviewed Publications (continued):

2.1.6 Wake, B.E., Sankar, N.L., and Lekoudis, S.G., "Computation of Rotor Blade Flows Using the Euler Equations". AIAA Journal of Aircraft, Vol. 23, No. 7, July 1986.

2.1.7 Wang, C. M. and Wu, J. C., "Numerical Solution of Navier-Stokes Problems using Integral Representation with Series Expansion," AIAA Journal Vol. 24, No. 8, pp. 1305-1312, August 1986.

2.1.8 Thompson, T. L., "Velocity Measurements near the Blade Tip and in the Tip Vortex Core of a Hovering Model Rotor," Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, December 1986.

2.1.9 Wake, B. E., "Solution Procedure for the Navier-Stokes Equations Applied to Rotors," Ph.D. Thesis, Georgia Institute of Technology, April 1987.

2.1.10 Sankar, N.L., and Tang, W., "Numerical Solution of Unsteady Viscous Flow Past Rotor Sections". AIAA Journal of Aircraft, June 1987. Submitted for publication.

2.1.11 Brand, A.G., Komerath, N.M. and McMahon, H. M., "A Laser Sheet Visualization Technique for Incompressible Vortex Wakes:. AIAA Preprint No. 88-0192.

2.1.12 Brand, A.G., McMahon, H. M. and Komerath, N.M., "Surface Pressure Measurements on a Body Subject to Vortex-Wake Interaction". Submitted to the AIAA Journal, August 1987.

2.1.13 Liou, S.D., Komerath, N.M., and McMahon, H.M., "The Velocity Field of a Lifting Rotor in Low-Speed Forward Flight". AIAA Preprint No. 88-0666.

2.1.14 Brand, A.G., Komerath, N.M., and McMahon, H.M., "Results from the Laser Sheet Visualization of an Incompressible Vortex Wake". Submitted to the Journal of Aircraft, January 1987.

2.1.15 Komerath, N. M., Liou, S.G., Brand. A.G., and McMahon, H.M., "A Study of the Encounter Between a Helical Vortex and a Circular Cylinder". Submitted to the Proceeding of the First National Fluid Dynamics Congress, December 1987.

2.1.16 Komerath, N.M., and Schreiber, O.A., "Implementation and Validation of a Wake Model for Low-Speed Forward Flight", Presented at the U.S. Army Aerostructures Directorate, NASA Langley Research Center, November 23, 1987.

2.1.17 Komerath, N.M., Thompson, T.L, Kwon, O.J., and Gray, R.B., "The Velocity Field of a Lifting Model Rotor Blade in Hover". To appear in the Journal of Aircraft, F/March 1988.

2.1 Peer Reviewed Publications (continued):

2.1.18 Thompson, T.L., Komerath, N.M., and Gray, R.B. "Visualization and Measurement of the Tip Vortex Core of a Rotor Blade in Hover". Accepted by the Journal of Aircraft.

2.2 Meeting Publications:

2.2.1 Wang, C.M., and Wu, J.C., "Numerical Solution of Navier-Stokes Problems using Integral Representations with Series Expansions," AIAA Paper 85-0034, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

2.2.2 Sankar, N.L., Wake, B.E., and Lekoudis, S.G., "Solution of the Unsteady Euler Equations for Fixed and Rotor Wing Configurations," AIAA Paper 85-0120, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

2.2.3 Wu, J.C., Sankar, N.L., and Hsu, T.M., "Unsteady Aerodynamics of an Airfoil Encountering a Passing Vortex," AIAA Paper 85-0203, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

2.2.4 Sankar, N.L., and Tang, W., "Numerical Solution of Unsteady Viscous Flow Past Rotor Sections," AIAA Paper 85-0129, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

2.2.5 Wake, B.E., Sankar, N.L., Lekoudis, S.G., and Gray, R.B., "The Prediction of Flow around Blade Tips," International Conference on Rotorcraft Basic Research, Research Triangle Park, NC, February 1985.

2.2.6 Wu, J.C., "Computational and Theoretical Studies of Unsteady Viscous Aerodynamics," Low Reynolds Number Aerodynamics Conference, Notre Dame University, South Bend, IN, June 1985.

2.2.7 Komerath, N.M., McMahon, H.M., and Hubbartt, J.E., "Aerodynamic Interactions Between a Rotor and Airframe in Forward Flight," AIAA Paper No. 1606, 18th Fluid Dynamics, Plasmadynamics and Lasers Conference, Cincinnati, OH, July 1985.

2.2.8 Komerath, N.M., Thompson, T. L., and Gray, R.B., "Velocity Measurements in the Near Wake of a Hovering Rotor", AIAA Paper 85-1675, presented at the 18th Fluid Dynamics, Plasmadynamics and Lasers Conference, Cincinnati, OH, July 1985.

2.2.9 Wang, C.M., Wu, J.C., and Sankar, N.L., "Unsteady Aerodynamics of Airfoils Oscillating In and Out of Dynamic Stall", AIAA Paper 85-4078. 3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 1985.

2.2.10 Wu, J.C., Hsu, T.M., Tang, W. and Sankar, N.L., "Viscous Flow Results for the Vortex-Airfoil Interaction Problem," AIAA Paper 85-4053. 3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 1985.

2.2 <u>Meeting Publications (continued)</u>:

2.2.11 Wake, B.E. Sankar, N.L., and Lekoudis, S.G. "Computation of Rotor Blade Flows Using the Euler Equations," AIAA Paper 85-5010. 3rd Applied Aerody-namics Conference, Colorado Springs, CO, October 1985.

2.2.12 McMahon, H.M., Komerath, N.M., and Hubbartt, J.E., "Studies of Rotor-Airframe Interactions in Forward Flight", AIAA Paper No. 85-50-15, 3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 1985.

2.2.13 Komerath, N.M., Thompson, T.L., and Gray, R.B., "Velocity Measurements in the Near Field of a Rotor Blade in Hover", AIAA Paper No. 85-5013, presented at the 3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 1985.

2.2.14 Leland, B., "Laser Sheet Visualization of Rotorcraft Flowfield Dynamics." Presented at the AIAA Southeastern Regional Student Conference, April 1986.

2.2.15 Wu, J. C., Wang, C. W., and Sankar, N. L., "Dynamic Stall of Oscillating Airfoils," 42nd Annual Forum of the American Helicopter Society, Washington, D. C., June 1986.

2.2.16 Sankar, N. L., and Tung, C., "Euler Calculations for Rotor Configurations in Unsteady Forward Flight," Proceedings of the 42nd Annual Forum of the American Helicopter Society, June 1986.

2.2.17 Brand A., G., Komerath, N. M., McMahon, H. M.: "Wind Tunnel Data from a Rotor Wake/Airframe Interaction Study." Wind Tunnel Report, Georgia Institute of Technology, July 1986.

2.2.18 Thompson, T. L., Kwon, O. J., Kemnitz, J. L., Komerath, N. M., and Gray, R. B., "Tip Vortex Core Measurements on a Hovering Model Rotor," AIAA Paper 87-0209, 25th Aerospace Sciences Meeting, Reno, NV, January, 1987.

2.2.19 Wu, J. C. and Hsu, T. M., "The Unsteady Forces and Moments Induced by Blade-Vortex Interaction," Proceedings of AHS Specialists' Meeting on Aerodynamics and Aeroacoustics, Arlington, TX, February 1987.

2.2.20 Wake, B. E. and Sankar, L. N., "Solutions of the Navier-Stokes Equations for the Flow about a Rotor Blade," Proceedings of the AHS Specialists Meeting on Aerodynamics and Aeroacoustics, Arlington, TX, February 1987.

2.2.21 Peters, D. A., "The Importance of Aerodynamics on Rotorcraft Dynamics," AHS National Specialists' Meeting on Aerodynamics and Acoustics, Arlington, Texas, February 1987.

2.2.22 Peters, D. A., "A Unsteady Aerodynamic Theory in Hover and in Forward Flight," Proceedings of the 43rd Annual Forum of the American Helicopter Society, St. Louis, MO, May 1987.

2.2 Meeting Publications (continued):

2.2.23 Tang, W. and Sankar, L. N., "Strong Blade-Vortex Interactions Including Collision," Submitted to the Forum on Unsteady Flow Separation, ASME Fluids Engineering Spring Conference, Cincinnati, OH, June 1987.

2.2.24 Wake, B. E., Sankar, L. N., Jiunnchi-Wu and Ruo, S. Y., "An Efficient Procedure for the Numerical Solution of Three-Dimensional Viscous Flows," AIAA Paper 87-1159, AIAA CFD Conference, Waikiki, HI, June 1987.

2.2.25 Wu, J. C., "Boundary Element Solution of Viscous Flow Problems," Proceedings of 3rd International Conference on Boundary Element Technology, Cambridge, MA, June 1987.

2.2.26 Peters, D. A., "Modeling Rotorcraft Aerodynamics," Sixth International Conference on Mathematical Modeling, St. Louis, MO, August 1987.

2.2.27 Komerath, N. M., Thompson, T. L., Kwon, O. J., and Gray, R. B., "The Velocity Field of a Lifting Model Rotor Blade in Hover." Accepted for publication in the Journal of Aircraft, 1987.

2.2.28 Brand, A. G. , Komerath, N.M., and McMahon, H.M., Results from Laser Sheet Visualization of an Incompressible Vortex Wake". AIAA Paper No. 88-0192, 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988.

2.2.29 Liou, S.F., Komerath, N.M., and McMahon, H.M, "The velocity Field of a Rotor in Low-Speed Forward Flight". AIAA Paper 88-0166, 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988.

2.2.30 Brand, A. G., Liou, S.F., Komerath, N.M, and McMahon, H.M., "Rotor-Airframe Aerodynamic Interaction Phenomena". Proceedings of the 2nd International Conference on Rotorcraft Basic Research, College Park, Maryland, February 1988.

2.2.31 Sankar, L.N. and Komerath, N.M., "Measurement and Computation of the Flow Around the Tip of a Lifting Rotor Blade in Hover," AIAA Paper 88-0047, 1988.

2.2.32 Narramore, J., Sankar, L.M., and Vermeland, R., "An Evaluation of a Navier-Stokes Code for Calculation of Retreating Blade Stall on a Helicopter Rotor", To be Presented at the 44th Annual Forum of the American Helicopter Society, 1988.

2.2.33 Sankar, N.L, and Komerath, N.M.;, "Measurement and Computation of the Velocity Field of a Rotor in Hover". AIAA 88-0047, 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988.

2.3 Contract Reports:

2.3.1 Brand, A. G. , Komerath, N.M., and McMahon, H.M., "Wind Tunnel Data from a Rotor Wake/Airframe Interaction Study", Data Report, Contract No. DAA29-82-K-0094, School of Aerospace Engineering, Georgia Institute of Technology, July 1986.

2.3 Contract Reports (Continued):

2.3.2 Komerath, N.M. and Schreiber, O.A., "Implementation and Validation of a Wake Model for Low-Speed Forward Flight,," Final Technical Report, NASA Grant NAG-1-693. GITAER 87-3, September 1987.

McMahon, H.M., Merati, P., and Yoo, K.M. "Mean Velocities and Reynolds Stresses in the Juncture Flow and in the Shear Layer Downstream of an Appendage", Final Report, ONR Contract N00014-85-K-0234, September 1987.

2.4 Student Special Problems:

2.4.1 Kemnitz, J.L. "Correcting LDV Data for Particle Inertia". M.S. Special Problem Report, Georgia Institute of Technology, School of Aerospace Engineering, August 1986.

2.4.2 Sullivan, A. "Application of Backsolving Technique to Correct LDV Data". M.S. Special Problem Report, Georgia Institute of Technology, School of Aerospace Engineering, August 1987.

2.4.3 Leland, B. "Determination of Rotor Tip Vortex TRajectories Using Synchronized Laser Screen Visualization". Special Problem Report, Georgia Institute of Technology, School of Aerospace Engineering, March 1986.

3. STRUCTURES AND MATERIALS:

3.1 Peer Reviewed Publications:

3.1.1 Hanagud, S.V., and Abhyankar, N.S. "A Numerical Scheme for the Study of Pointing Effect in Wave Propagation Problems with Finite Boundaries," International Journal of Nonlinear Mechanics, Vol. 19, No. 6, December 1984.

3.1.2 Jonnalagadda, V.R.P., and Pierce, G.A., "Nonlinear Deformation of Rotating Beams - An Alternate Method of Formulation," Journal of the American Helicopter Society, Vol. 30, No. 2, April 1985.

3.1.3 Hanagud, S.V., Meyyappa, and Craig, J.I., "Method of Multiple Scales and Identification of Nonlinear Structural Dynamic Systems," AIAA Journal, Vol. 23, No. 5, May 1985.

3.1.4 Hodges, D. H.; Peters, D. A.; Pierce, G. A.; and Jonnalagadda, V. R.P.: Comment on "Nonlinear Deformation of Rotating Beams - An Alternate Method of Formulation." Journal of the American Helicopter Society, vol. 31, no. 3, July 1986.

3.1.5 S,. Hanagud, M. Meyyappa, Y. P. Cheng, and J. I. Craig, "Identification of Structural Dynamic Systems with Nonproportional Damping," AIAA Journal, Vol. 24, Nov. 1986, pp. 1880-1882.

3.1 Peer Reviewed Publications (continued):

3.1.6 Hodges, R.V., Nixon, M.W. and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastran Shell Element Model," NASA Technical Memorandum - 89024, January 1987.

3.1.7 Bauchau, O., Coffenberry, B.S. and Rehfield, L.W., "Composite Box Beam Analysis: Theory and Experiments," Journal of Reinforced Plastics and Composites, January 1987.

3.1.8 Reddy, A.D., Rehfield, L.W., Brutomesso, R.I., and Krebs, N.E., "Local Buckling and Crippling of Thin-Walled Composite Structures under Axial Compression". AIAA Journal of Aircraft, 1987. Submitted for publication.

3.1.9 Hodges, D. H.: Finite Rotation and Nonlinear Beam Kinematics. Vertica, vol. 11, no. 1/2, 1987, pp. 297 - 307.

3.1.10 Hodges, D. H.: Nonlinear Beam Kinematics for Small Strains and Finite Rotations. Vertica, vol. 11, no. 3, 1987.

3.1.11 Degener, M.; Hodges, D. H.; and Petersen, D.: "Analytical and Experimental Study of Beam Torsional Stiffness with Large Elongation." Journal of Applied Mechanics, 1987, submitted for publication.

3.1.12 Danielson, D. A.; and Hodges, D. H.: "Notes on Nonlinear Beam Theory." Journal of Applied Mechanics, 1987, submitted for publication.

3.2 Meeting Publications:

3.2.13 Hanagud, S.V., Meyyappa, M., and Craig, J.I., "Structural Dynamic Physical Models of Helicopters by Identification Technique," Ninth European Rotorcraft Forum, Stresa, Italy, September 1983.

3.2.14 Hanagud, S.V., Meyyappa, M., Cheng, P., and Craig, J.I., "Identification of Structural Dynamic Systems with Nonproportional Damping," AIAA / ASME / ASCE / AHS 25th Structures, Structural Dynamics and Materials and Materials Conference, Palm Springs, CA, May 1984.

3.2.15 Hanagud, S.V., and Chen, H.P., "A Two-Step Version of Strang-Gottlieb Techniques for Deformable Lagrangian Meshes," U. S. Army Conference on Numerical Methods, Rensselaer Polytechnic Institute, Troy, NY, August 1984.

3.2.16 Reddy, A.D., Rehfield, L.W., Bruttomesso, R.I., and Krebs, N.E., "Local Buckling and Crippling of Thin-Walled Composite Structures under Axial Compression," 26th AIAA/ASME/ASCE/AHS SDM Conference, AIAA Paper 85-0672 CP, Orlando, FL, April 1985.

3.2.17 Hanagud, S.V., Chen, H.P., and Sriram, P., "A Study of the Static Post-Buckling Behavior of Composite Sandwich Plates," International Conference on Rotorcraft Basic Research, Research Triangle Park, NC, February 1985.

3.2 <u>Meeting Publications (continued)</u>:

3.2.18 Hanagud, S.V., Smith, C.V., and Chattopadhyay, A., "Optimal Design of a Vibrating Beam with Coupled Bending and Torsion," 26th AIAA / ASME / ACSE / AHS SDM Conference, Orlando, FL, April 1985.

3.2.19 Hanagud, S.V., Obal, M.W., and Meyyappa, M., "Electronic Damping Techniques and Active Vibration Control," 26th AIAA / ASME / ASCE / AHS SDM Conference, Orlando, FL, April 1985.

3.2.20 Hanagud, S.V., Chander, R., and Abhyankar, N.S., "Identification and Nonlinear (Chaotic) Vibration of Buckled Beams with Stops," 26th AIAA / ASME / ASCE / AHS SDM Conference, Orlando, FL, April 1985.

3.2.21 Hanagud, S.V., Craig, J.I., Schrage, D.P., and Sriram, P., "Crashworthy Design of Rotorcraft: A Basic Research Approach," 41st American Helicopter Society Forum, Fort Worth, TX, May 1985.

3.2.22 Reddy, A.D., Rehfield, L.W., and Bruttomesso, R.I., "Local Crippling and Postcrippling Behavior of Graphite/Epoxy Thin-Walled Airframe Members," 41st Annual American Helicopter Society Forum, Fort Worth, TX, May 1985.

3.2.23 Rehfield, L.W., "Design Analysis Methodology for Composite Rotor Blades," 7th DoD/NASA Conference on Fibrous Composites, Denver, CO, June 1985.

3.2.25 Hanagud, S.V., "Elastic Fuselage Modes and Higher Harmonic Control," paper presented and published in the proceedings of the Eleventh European Rotorcraft Forum, London, September 1985.

3.2.26 Bauchau, O., Coffenberry, B.S., and Rehfield, L.W., "A Comparison of Composite Rotor Blade Models," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, GA, December 1985.

3.2.27 Hodges, R.V., Nixon, M.W., and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastran Shell Element Model," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, GA, December 1985.

3.2.28 Rehfield, L.W., "Shear Center, Elastic Axis and Their Usefulness in Evaluating Composite Rotor Blade Response," ARO Dynamics and Aeroelastic Stability Modeling of Rotor Systems Workshop, Georgia Institute of Technology, Atlanta, GA, December 1985.

3.2.29 Hanagud, S.V., "Finite Difference Techniques for Rotor Blade Equations," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, GA, December 4-5, 1985.

3.2 Meeting Publications (continued):

3.2.30 Hanagud, S.V., Chattopadhyay, A., Zhang, J., and Wang, Y., "Mechanism of Energy Absorption via Buckling: An Analytical Study," AHS National Rotorcraft Specialists Meeting on Crash-worthy Design of Rotorcraft, Georgia Institute of Technology, Atlanta, GA, April 1986.

3.2.31 Suram, P., Hanagud, S.V. and Ranson, W.F., "Wholefield Displacement Measurements using Speckle Image Processing Techniques for Crash Tests." AHS National Specialists Meeting on Crashworthy Design of Rotorcraft, Atlanta, GA, April 1986.

3.2.32 Craig, N., Hanagud, S., Zhon, W and Suram, P., "Correlation of Experimental Static and Dynamic Response of Simple Structural Components.

3.2.33 Hanagud, S.V. and Sankar, S., "Kane's Method for Analyzing Crash Sequences and Crashworthy Design," AHS National Specialists Meeting on Crashworthy Design of Rotorcraft, Georgia Institute of Technology, Atlanta, GA, April 1986.

3.2.34 Chattopadhyay, A., Hanagud, S. V., and Smith, C. V. Jr., "Minimum Weight Design of a Structure with Dynamic Constraints and a Coupling of Bending and Torsion," AIAA/ASME/ASCE/AHS SDM Meeting, San Antonio, TX, May 1986.

3.2.35 Rehfield, L.W. and Reddy, A.D., "Observations on Compressive Local Buckling, Postbuckling and Crippling of Graphite-Epoxy Airframe Structure," AIAA/ASME/ASCE/AHS 27th SDM Conference, San Antonio, TX, May 1986.

3.2.36 Hanagud, S., Meyyappa, M., and Craig, J. I., "Basic Research in Structural Dynamic System Identification," 42nd Annual Forum of the American Helicopter Society, Washington, D.C., June 1986.

3.2.37 Hanagud, S., Meyyappa, M., Sankar, S., and Craig, J. I., "A Coupled Rotor/Airframe Vibration Model with Higher Harmonic Control Effects," 42nd Annual Forum of the American Helicopter Society, Washington, D. C., June 1986.

3.2.38 Rehfield, L.W., "Some Observations on the Behavior of the Langley Model Rotor Blade," USA Aerostructures Directorate, Langley Research Center, Hampton, VA, July 1986.

3.2.39 Chan, W.S. and Rehfield, L.W., "Analysis, Prediction and Prevention of Edge Delamination in Rotor System Structures," RPI Workshop on Composite Materials and Structures for Rotorcraft, Troy, NY, September 1986.

3.2.40 Rehfield, L.W., Reddy, A.D. and Daniel W.K., "Postbuckled Composite Primary Structure: Creating the Technology Base," RPI Workshop on Composite Materials and Structures for Rotorcraft, Troy, NY, September 1986.

3.2 <u>Meeting Publications (continued)</u>:

3.2.41 Rehfield, L. W. and Atilgan, A. R., "A Structural Model for Composite Rotor Blades and Lifting Surfaces," Paper AIAA 87-0769-CP, 28th SDM Conference, Monterey, CA, April 1987.

3.2.42 Hanagud, S. and Obal, M. W., "Optimal Vibration Control by the Use of Piezoceramic Sensors and Drivers," 28th AIAA/ASME/AHS/ASEE SDM Conference, Monterey, California, April 1987.

3.2.43 Hanagud, S. and Glass, B. J., "Structural Dynamic Model Identification Using Heuristic Search," 28th AIAA/ASME/AHS/ASEE SDM Conference, Monterey, California, April 1987.

3.2.44 Rehfield, L.W. and Atilgan, A.R., "A Structural Model for Composite Rotor Blades and Lifting Surfaces," AIAA-87-0768-CP, 28th SDM Conference, Monterey, CA, April 1987.

3.2.45 Hinnant, H. E.; and Hodges, D. H.: "Application of GRASP to Nonlinear Analysis of a Cantilever Beam." 28th Structures, Structural Dynamics and Materials Conference and Dynamics Specialists Conference (Part II), Monterey, CA, April 1987, AIAA Paper 87-0953.

3.2.46 Chan, W. S., Rehfield, L. W. and O'Brien, T. K., "Analysis, Prediction and Prevention of Edge Delamination in Rotor System Structures," 43rd Annual Forum of the American Helicopter Society, St. Louis, MO, May 1987.

3.2.47 Kunz, D.L. and Hodges, D.H., "Analytical Modeling of Helicopter Static and Dynamic Induced Velocity in GRASP", Proceedings of the 6th International Conference on Mathematical Modeling, St. Louis, Mo, August 4-7, 1987.

3.2.48 Hodges, D.H., "Nonlinear Beam Kinematics for Small Strains and Finite Rotations", Presented at the Army Research Office Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotor Systems, Florida Atlantic University, Boca Raton, FL, November 18-20, 1987.

3.2.49 Hodges, D.H., "Analytical and Experimental Study of Beam Torsional Stiffness with Large Axial Elongation", Presented at the Army Research Office Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotor Systems, Florida Atlantic University, Boca Raton, FL, November 18-20, 1987.

3.2.50 Hodges, D.H., "Review of Composite Rotor Blade Modeling", Presented at the Army Research Office Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotor Systems, Florida Atlantic University, Boca Raton, FL, November 18-20, 1987.

4. AEROELASTICITY AND DYNAMICS

4.1 Peer Reviewed Publications:

4.1.1 Hamouda, M. H. and Pierce, G. A., "Helicopter Vibration Suppression using Simple Pendulum Absorbers on the Rotor Blade," Journal of the American Helicopter Society, Vol. 29, No. 3, July 1984.

4.1.2 Jonnalagadda, V.R.P., "A Derivation of Rotor Blade Equations of Motion in Forward Flight and Their Solution," Ph.D. Thesis (Advisor: G. A. Pierce), Georgia Institute of Technology, Atlanta, GA, 1985.

4.1.3 Pierce, G. A. and Klein, S. S., "A Unique Approach to Aeroelastic Testing of Scaled Rotors," Twelfth European Rotorcraft Forum, Garmisch-Partenkirchen, Germany, September 1985, submitted to Vertica 1987.

4.1.4 Nygren, K. P., "An Investigation of Helicopter Higher Harmonic Control using a Dynamic System Coupler Simulation," Ph.D. Thesis, (Advisor-Schrage, D. P.) Georgia Institute of Technology, December 1986.

4.1.5 Crespo da Silva, M. R. M.; and Hodges, D. H.: Nonlinear Flexure and Torsion of Rotating Beams with Application to Helicopter Rotor Blades - I. Formulation. Vertica, vol. 10, no. 2, 1986, pp. 151 - 169.

4.1.6 Crespo da Silva, M. R. M.; and Hodges, D. H.: Nonlinear Flexure and Torsion of Rotating Beams with Application to Helicopter Rotor Blades - II. Response and Stability Results. Vertica, vol. 10, no. 2, 1986.

4.1.7 Peters, D. A., Rossow, H., Korn, A. and Ko, T., "Design of Helicopter Rotor Blades for Optimum Dynamic Characteristics," Computers and Mathematics with Applications, Vol. 12A, No. 1, 1986.

4.1.8 Peters, D. A. and Karunamoorthy, S., "Use of Hierarchical Elastic Blade Equations and Automatic Trim for Helicopter Vibration Analysis," Vertica, Vol. 10, No. 4, December 1986.

4.1.9 Peters, D. A. and Chouchane, M., "Effect of Dynamic Stall on Helicopter Trim and Flap-Lag Response," Fluids and Structures, Vol. 1, No. 1, 1986.

4.1.10 Danielson, D. A.; and Hodges, D. H.: Nonlinear Beam Kinematics by Decomposition of the Rotation Tensor. Journal of Applied Mechanics, Vol. 54, No. 2, 1987.

4.1.11 Taylor, D. J., "A Method for the Efficient Calculation of Elastic Rotor Blade Dynamic Response in Forward Flight," Ph.D. Thesis (Advisor: G. A. Pierce) Georgia Institute of Technology, Atlanta, GA, 1987.

4.1 Peer Reviewed Publications (continued):

4.1.12 Hodges, D. H.; Hopkins, A. S.; Kunz, Donald L.; and Hinnant, H. E.: "Introduction to GRASP - General Rotorcraft Aeromechanical Stability Program - A Modern Approach to Rotorcraft Modeling." Journal of the American Helicopter Soc., Vol. 32, No. 2, April 1987.

4.1.13 Hodges, D. H.; Hopkins, A. S.; and Kunz, D. L.: "Analysis of Structures with Rotating, Flexible Substructures Applied to Rotorcraft Aeroelasticity in GRASP." AIAA Journal, 1987, submitted for publication.

4.1.14 Nygren, K.P. and Wasikowski, M.E., "Application of Frequency and Time Domain Cost Functionals to Active Vibration Control of an OH-6 Helicopter in Forward Flight", Proceedings of the AHS Specialists Meeting on Rotorcraft Flight Controls and Avionics, Cherry Hill, NJ, October 13-15, 1987; submitted for publication in Journal of Sound and Vibration.

4.1.14 Hinnant, H. E.; and Hodges, D. H.: "Application of GRASP in Nonlinear Analysis of a Cantilever Beam." AIAA Journal, 1987, submitted for publication.

4.1.15 Stephens, W. B. and Peters, D. A., "Rotor Body Coupling Revisited," Journal of the American Helicopter Society, Vol. 32, No. 1, January 1987.

4.1.16 Peters, D. A. and Chouchane, M., "Effect of Dynamic Stall on Helicopter Trim and Flap-Lag Response," Fluids and Structures, Vol. 2, No. 1, 1987.

4.2 Meeting Publications:

4.2.1 Peters, D. A. and Ventura, L., "Application of Various Solution Techniques to the Calculation of Transonic Flutter Boundaries," Presented at the ASME Vibration and Sound Conference, Cincinnati, Ohio, September 1985.

4.2.2 Jonnalagadda, V.R.P., and Pierce, G.A., "Effect of Cyclic Pitch Variations on Hingeless Rotor Blade Stability," presented at the ARO Dynamics and Aeroelastic Stability Workshop, Atlanta, GA, December 1985.

4.2.3 Hanagud, S., Yillikci, Y. K., and Sankar, N. L., "Finite Difference Techniques for Rotor Blade Equations," ARO/CERWAT Conference on Dynamics and Aeroelastic Stability, Modeling and Rotor Systems, Georgia Institute of Technology, December 1985.

4.2.4 Gaonkar, G. H. and Peters, D. A., "Review of Floquet Theory in Stability and Response Analyses of Dynamic Systems with Periodic Coefficients," Recent Trends in Aeroelasticity, Structures, and Structural Dynamics, Gainesville, FL, February 1986.

4.2.5 Gaonkar, H. and Peters, D. A., "Review of Dynamic Inflow Modeling for Rotorcraft Flight Dynamics," AIAA 27th SDM Conference, San Antonio, TX, May 1986.

4.2.6 Karunamoorthy, S. and Peters, D. A., "Use of Hierarchical Elastic Blade Equations and Automatic Trim for Helicopter Vibration Analysis," 42nd Annual Forum of the American Helicopter Society, Washington, D.C., June 1986.

4.2 Meeting Publications (continued):

4.2.7 Peters, D. and Izadpanah, A., "Generalization of Hamilton's Law to a Bilinear Formulation with Application to Helicopter Stability," The First World Congress on Computational Mechanics, Austin, Texas, September 1986.

4.2.8 Ormiston, R. A.: Warmbrodt, W. G.; Hodges, D. H.; and Peters, D. A.: "Rotorcraft Aeroelastic Stability - Twenty Years of Army/NASA Research 1967 - 1987." NASA/Army Rotorcraft Technology Conference, NASA Ames Research Center, Moffett Field, CA, March 1987.

4.2.9 Danielson, D. A.; and Hodges, D. H.: "Notes on Nonlinear Beam Theory." 28th Structures, Structural Dynamics and Materials Conference (Part I),

4.2.10 Hodges, D. H.; Hopkins, A. S.; and Kunz, D. L.: "Analysis of Structures with Rotating, Flexible Substructures Applied to Rotorcraft Aeroelasticity in GRASP." 28th Structures, Structural Dynamics and Materials Conference and Dynamics Specialists Conference (Part II), Monterey, CA, April 1987, AIAA Paper 87-0952.

4.2.11 Pierce, G. A., "Dynamic Testing Techniques for Controlled Excitation of Scaled Rotors," 5th International Modal Analysis Conference, London, England, April 1987.

4.2.12 Kunz, D. L.; and Hodges, D. H.: "Correlation of Analytical Calculations from GRASP with Torsionally-Soft Rotor Data." 43rd Annual Forum of the American Helicopter Society, St. Louis, MO, May 1987.

4.2.13 Peters, D. A., "A Closed-Form Unsteady Aerodynamic Theory for Lifting Rotors in Hover and Forward Flight," 43rd Annual Forum of the American Helicopter Society, St. Louis, MO, May 1987.

4.2.14 Hanagud, S., Yillickei, Y. and Sankar, L. N., "Finite Difference Techniques for Rotor Blade Aeroelasticity," European Rotorcraft Forum, France, September 1987.

4.2.15 Prasad, J.V.R. and Wasekowski, M.E., "Active Vibration Control Using Reduced-Order Models," Presented at the Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, sponsored by the U.S. Army Research Office, Boca Raton, FL, November 18-20, 1987.

5. FLIGHT MECHANICS AND CONTROL

5.1 Peer Reviewed Publications:

5.1.1 Menon, P. K. A., Kelley, H. J., and Cliff, E. M., "Optimal Symmetric Flight with an Intermediate Vehicle Model," Journal of Guidance, Control and Dynamics, Vol. 8, May-June 1985.

5.2 Meeting Publications (continued):

5.1.2 Moerder, D. D., Calise, A. J., "Two-Time Scales Stabilization of Systems with Output Feedback," AIAA Journal of Guidance and Control and Dynamics," Vol. 8, No. 6, November-December, 1985.

5.2.3 Calise, A. J., Moerder, D. D., "Optimal Output Feedback Design of Systems with Ill-Conditioned Dynamics," Automatica, Vol. 21, No. 3, 1985.

5.2.4 Gilmore, J. F. and Semeco, A. C., "Knowledge-based Approach toward Developing an Autonomous Helicopter System," Optical Engineering, Vol. 25, No. 3, March 1, 1986.

5.2.5 Menon, P. K. A., et. al., "Flight Test Trajectory Controllers for Aircraft," Journal of Guidance, Control and Dynamics, Vol. 10, Jan.-Feb. 1987, pp. 67-72.

5.2.6 Moerder, D. D., Calise, A. J., "Convergence of a Numerical Algorithm for Calculating Output Feedback Gains," IEEE Trans. Auto Control, Vol. AC-30, September 1985.

5.2.7 Kramer, F. S., Calise, A. J., "Fixed Order Dynamic Compensation for Multi-variable Linear Systems, "AIAA Guid., Na., and Control, Conf., Williamsburg, VA, August 1986 (to appear in the AIAA Journal of Guid., Cont., and Dynamics).

5.2.8 Siciliano, B., Calise, A. J., Jonnalagadda, V. R. P., "Optimal Output Fast Feedback in Two-Time Scale Control of Flexible Arms," IEEE Conference on Decision and Control, Athens, Greece, December 1986.

5.2.9 Hanagud, S., Obal, M. W., Calise, A. J., "Optimal Vibration Control by the Use of Piezoceramic Sensors and Actuators," AIAA Struct. Dyn. Spec. Meeting, Monterey, CA, April 1987.

5.2.10 Nygren, K. P., "Fixed-Gain Versus Adaptive Higher Harmonic Control: An Analytical Simulation," Southeast AHS Lichten Award Winner, December 1986. Paper and presentation given at the 42nd Annual Forum of The American Helicopter Society, May 1987.

5.2.11 Menon, P. K. A. and Briggs, M. M., "A Midcourse Guidance Law for Air-to-Air Missiles," AIAA Guidance, Navigation and Control Conference, Monterey, Aug. 15-17, 1987.

5.2.12 Schrage, D.P. and Heiges, "The Integration of Knowledge-Based Expert System and Rotorcraft Simulation Models", presented at the AHS National Specialists' Meeting on Rotorcraft Flight Controls and Avionics, Cherry Hill, H.J., October 13-15, 1987.

5.2.13 Schrage, D.P., Nygren, K.P. and Wasikowski, M.E., "Application of Frequency and Time Domain Cost Functionals to Active Vibration Control of an OH-6 Helicopter in Forward Flight", presented at the AHS National Specialists' Meeting on Rotorcraft Flight Controls and Avionics, Cherry Hill, H.J., October 13-15, 1987.

6. DESIGN:

6.1 Peer Reviewed Publications:

6.1.1 Schrage, D. P., "Use of Rotorcraft Computer Analysis for U. S. Government Design Assessment," International Journal of Computers and Mathematics with Applications, Vol. 12A, No. 1, February 1986.

6.1.2 Berry, J. and Schrage, D. P., "Rotor Design for Maneuver Performance, submitted to Vertica. Presented at Twelfth European Rotorcraft Forum, Garmisch - Partenkirchen, Federal Republic of Germany, September 1986.

6.2 Meeting Publications:

6.2.1 Schrage, D. P. and Meyer, S. A., "Logistics Supportability Considerations During Conceptual and Preliminary Design," Presented at AIAA/AHS/ASEE Aircraft Systems, Design and Technology Meeting, November 1985, subsequently published in Vertiflite, Vol. 32, March-April 1986.

6.2.2 Schrage, D. P. and Meyer, S. A., "VTOL Operational Considerations and Their Impact on Future Military Design Requirements," AIAA/AHS/ASEE Aircraft Systems, Design & Technology Meeting, October 1986, Dayton, OH, AIAA #86-2649.

6.2.3 Schrage, D. P. and Meyer, S. A., "Rotorcraft Preliminary Design Education," AIAA/AHS/ASEE Aircraft Systems, Design and Technology Meeting, October 1986, Dayton, OH, AIAA paper #86-2748.

6.2.4 Meyer, S. A. and Schrage, D. P., "Parametric Cost Analysis of Helicopters and Advanced Rotorcraft Designs," Ninth Annual Symposium of The International Society of Parametric Analysts, San Diego, CA, May 1987.

6.2.5 Schrage, D.P. and Bates, P.R., "The Configurator and Conceptual Design for Rotary Wing Aircraft", AIAA Paper No. AIAA-87-2891, presented at AIAA / AHS / ASEE Aircraft Design, Systems, and Operations Meeting, St. Louis, MO, September 14-16 1987.

7. OTHER ROTORCRAFT RELATED

7.1 Meeting Publications:

7.1.1 Gray, R. B., "Graduate Rotorcraft Programs at Georgia Tech," ASEE Annual Conference, Salt Lake City, UT, June 1984.

7.1.2 Meyer, S. A., "China: Opening an Immense New Market," Vertiflite, Vol. 32, Number 3, May/June 1985.

7.1 Meeting Publications (continued):

7.1.3 Schrage, D. P., "Air Warfare: Helicopters and the Battlefield," Journal of Defense and Diplomacy, Vol. 3, No. 5, May 1985.

7.1.4 Meyer, S. A., "Universities, Cornerstone of the Rotary Wing Technology Base," Vertiflite, Vol. 31, Number 4, July/August 1985.

7.1.5 Schrage, D. P., Michelsen, R., and Gilmore, J. F., Georgia Tech Proposal: Technical Demonstration of an Autonomous Helicopter System, July 1986.

7.1.6 Schrage, D. P., Gessow, A., Loewy, R., "The U. S. Army Centers of Excellence Program in Review," Vertiflite, Vol. 32, Number 7, November/December 1986.

7.1.7 Meyer, S. A. and Schrage, D. P., "Aerospace Engineering: Pushing the Limit of Man's Imagination," Engineering Horizons, Spring 1987.

APPENDIX A

Scientific Personnel Supported by this Project

Co-Principal Investigators:

R. B. Gray
D. P. Schrage

Faculty:

R. B. Gray
D. P. Schrage
J. I. Craig
S.V. Hanagud
N. Komerath
H.M. McMahon
D.A. Peters
G.A. Pierce
L.W. Rehfield
N.L. Sankar
J.C. Wu

Research Engineers:

S.S. Klein
R. Latham
S.A. Meyer
M. Meyyappa
W. Tang

Research Associates:

J. Caudell
H. Meyer

Post Doctors:

V.R. Anand
T.M. Hsu
C. Wang

Fellows:

Ph.D.	A.G. Brand	M.W. Heiges
	D.N. Mavris	D. J. Taylor
	B. Wake	M.E. Wasikowski

Graduate Research Assistants:

Ph.D.	R. Chander	M. Hashemi-Kia
	C. He	V.M. Kaladi
	Y.K. Kim	O.J. Kwon
	S.G. Liou	M.T. Patterson
	S. Sarkar	P. Sriram
	I. Tuncer	C.C. Won
	Y.K. Yillicki	W. Zhou
M.S.	B. Glass	R. Kisor
	L.S. Mayer	H.E. Mersinoglou
	R. Srivastava	

Contributors not supported by project funds:

Faculty:	A. J. Calise
	D.H. Hodges
	P.K.A. Menon
Research Engineer:	V.R.P. Jonnalagadda
M.S. Students:	W.P. Crisler
	O. Schreiber

APPENDIX B

DEGREES AWARDED

NAME	DEGREE - DATE	LAST KNOWN AFFILIATION
V.R. Anand	PhD - Dec 1982	Georgia Tech
Jerry W. Anders	MS - Jun 1987	Lockheed-Georgia
A.R. Atilgan	MS - Jun 1987	Georgia Tech
Gilbert E. Boen	MS - Mar 1985	USA AVSCOM
A.G. Brand	MS - Sep 1985	PhD Cand. Ga Tech
T. Boyd	MS - Sep 1983	US Air Force
C. Boyette	MS - Dec 1983	McDonnell Douglas HC
C. Brevoort	MS - Sep 1983	Lockheed Georgia
CPT C.N. Cardinal	MS - Jun 1984	US Army
H.P. Chen	PhD - Dec 1983	Georgia Tech
Y.P. Cheng	PhD - Mar 1987	Georgia Tech
MAJ M. Clifford	MS - Dec 1982	US Army
J.E. Corban	BAE - Jun 1983	McDonnell Douglas HC
	MS - Sep 1986	PhD Cand. Ga Tech
W.P. Crisler	MS - Jun 1987	US Air Force
W.K. Daniel	MS - Dec 1986	Vought Corporation
P.L. Elliot, III	BAE - Jun 1983	Boeing Vertol Co.
K. Engelhart	MS - Sep 1983	McDonnell Douglas HC
C. Fouts	MS - Sep 1986	General Dynamics
P.J. Georges	MS - Sep 1984	
C. Grimmell	MS - Jun 1984	General Dynamics
B.A. Gustavson	MS - Sep 1982	Kaman Aerospace
J.W. Harding	MS - Sep 1986	McDonnell Douglas HC
M. Hashemi-Kia	MS	PhD Cand. Ga Tech
MAJ W.J. Hatch	MS - Jun 1984	US Army
M.W. Heiges	MS - Sep 1986	PhD Cand. Ga Tech
M.S. Huang	MS - Jun 1987	Georgia Tech
J.A. Humphries	MS - Jun 1984	US Air Force
A. Izadpanah	PhD - Dec 1986	NASA Langley
R. Jolly	MS - Sep 1986	
V.R.P. Jonnalagadda	MS - Sep 1983	
	PhD - Sep 1985	Georgia Tech
V.M. Kaladi	MS - Sep 1985	PhD Cand. Ga Tech
J.L. Kemnitz	MS - Sep 1986	Honeywell Inc., Minneapolis, MN
Y.K. Kim	MS - Sep 1985	PhD Cand. Ga Tech
S.S. Klein	MS - Mar 1987	Georgia Tech
S.G. Liou	MS - Sep 1985	PhD Cand. Ga Tech
L.S. Mayer	MS - Dec 1986	
D. Mavris	MS - Sep 1985	PhD Cand. Ga Tech
CPT W. McArthur	MS - Mar 1983	US Army
LTC K.P. Nygren	PhD - Dec 1986	USMA Faculty
P. Oliver	MS - Jun 1985	McDonnell Douglas HC
D. O'Neil	MS - Sep 1984	McDonnell Douglas HC
T. Parham	MS - Sep 1983	Bell Helicopter Textron
M.T. Patterson	MS - Sep 1986	PhD Cand. Ga Tech

M. Pollack	BAE - Jun 1986	MS Cand. Ga Tech Graduate Co-op Sikorsky Aircraft
G. Power	MS - Sep 1983	United Technologies Research Center
D. Pritchard	MS - Sep 1984	PhD Cand. Ga Tech Graduate Co-op McDonnell Douglas HC
J. Rogers	MS - Sep 1983	General Dynamics
O. Schreiber	MS - Sep 1986	PhD Cand. Ga Tech
S. Sparks	MS - Sep 1983	United Technologies Research Center
R. Srivastava	MS - Dec 1986	Georgia Tech
Carina M. Tan	MS - Mar 1987	NASA Ames
D.J. Taylor	MS - Sep 1984	
	PhD - Mar 1987	USA AVSCOM
T. Thompson	MS - Sep 1983	
	PhD - Dec 1986	McDonnell Douglas HC
R.R. Tipton	MS - Aug 1983	McDonnell Douglas HC
B. Wake	MS - Sep 1984	
	PhD - Mar 1987	United Technologies Research Center
M.E. Wasikowski	MS - Sep 1986	PhD Cand. Ga Tech
T. Wey	PhD - Dec 1983	Lockheed-EMSCO, Inc.

APPENDIX C

DISTINGUISHED FELLOWSHIP PROGRAM

One of the most significant accomplishments of CERWAT during its first five years has been the quality and quantity of U.S. citizens that have entered the rotary wing field. The magnet that has attracted them to rotary wing has been the Distinguished Fellowship Program. The CERWAT fellows, which numbered a total of sixteen for the first five years, came from a variety of sources. Many were the top graduates in our undergraduate program who took Robin Gray's "Introduction to Propellor and Rotor Theory" their senior year and then entered the CERWAT program. Some came from other outstanding engineering universities, especially once the CERWAT reputation was established. Still others came from the rotorcraft industry which has provided a natural means for interaction. All of the students awarded fellowships have been outstanding with greater than 3.5 out of 4.0 GPA's. All had expressed an intent of obtaining a Ph.D. degree. Some were not awarded fellowships their first year and had to demonstrate their abilities and rotary wing interest. Our goal has been to have one CERWAT fellow per research task with additional graduate research assistants (GRA's) as required. We plan to follow the same successful procedure during the next five year program. We have an outstanding group of graduate students entering next fall, many applying based upon CERWAT's reputation. A summary of the procedure follows:

1. Principle Investigators nominate candidates for CERWAT Fellowships to the Technical Director. Minimum criteria are:

   a. Minimum GPA of 3.5 out of 4.0 for undergraduate work. Exceptions can be made for candidates with extensive rotary wing experience and outstanding recommendations from their former employers,

   b. Candidate must express an intent to continue pursuit of a Ph.D. degree;

2. A CERWAT Review Board consisting of the Technical Director, Administrative and Finance Director, and one principle investigator from each discipline (Table 2) reviews the candidates' applications and selects the CERWAT Fellows; and

3. CERWAT Fellows' progress is checked each year by the Technical Director using the School of Aerospace Engineering's standard graduate student evaluation form which is submitted each quarter.